Keeping an Eye on Reliability

The Organizational Requirements of Future Renewable Energy Systems

Proefschrift

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Before you lies four years of work all rolled into one document. It is the result of a journey into the world of the organizational requirements of infrastructure reliability, a topic far removed from my studies of political science and international and European relations and which I stumbled into through the avenue of energy geopolitics and the promises of renewable energy. It is also the consequence of a predominant focus in the literature about future renewable energy systems on the technical development and market deployment of renewable energy sources and their societal acceptance. Nobody seemingly cares to think about the necessities of operating such technical systems once they are in place; what are their institutional requirements and what (geo)political implications might they have? Now, at the end of the journey, it is time to express my gratitude for the support I received along the way.

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Introduction

1. The Organizational Requirements of Reliability and the Challenge of Renewables

Modern economies depend greatly on the well-functioning of their energy infrastructures. Without a reliable supply of energy, industrial machinery, agricultural equipment, transportation, household appliances, communications, and PCs all come to a halt. Moreover, the effect of interruptions on social welfare may be very costly. The Electric Power Research Institute estimates, for example, that the annual cost of electricity interruptions in the US is between 119 and 188 billion dollars (EPRI 2001, 11). Consequently, policy makers and industry incumbents have traditionally kept a close eye on reliability, i.e. "the ability of [an energy] system to deliver the product (or service) transported over the network without interruption and without deterioration of its quality" (CPB 2004, 18).

Over the last decades, our understanding of energy infrastructure reliability has undergone some profound changes. "Until about a decade ago, most infrastructures were run as public monopolies, dominated by an engineering culture, with an almost exclusive focus on the technical assets" (Weijnen and Bouwmans 2006, 127). This meant that "[a]ccident investigations remained largely limited to the discovery of the direct causes of accidents" (De Bruijne 2006, 52), i.e. the technical failures in pipelines, wires, pressure stations, generation plants, etc. caused by natural disasters, human errors, (lack of) maintenance work, and capacity overload. Over the last decade, however, the operation of energy infrastructures has become more complex because of liberalization, privatization, and unbundling. In addition, our understanding about the interdependence and co-evolution of technology, actors and institutions shaped a perspective of energy infrastructures as socio-technical systems (Nelson 1994; Perez 2001; Murmann 2003; Geels 2002 and 2004). In turn, our understanding of reliability changed. It became increasingly clear to researchers and experts that "accidents and reliability issues related to the operation of technologies, although perhaps directly caused by technical or human failures, often have deeper, less visible causes" (De Bruijne 2006, 52). The occurrence of massive failures[1] seemed to be largely dependent on the absence of adequate coordination among actors to prevent small mistakes from becoming big disasters (Perrow 1999a, 1999b). The ability to communicate and coordinate effectively, in turn, seemed largely dependent on the organizational structure within which energy producers, transmission and distribution companies, retailers, and regulators interacted (Grabowski and Roberts 1996; Bourrier 2005). For example, while vertically integrated structures may be appropriate for centralized top-down coordination and for streamlining frequent and complex interactions, more horizontal structures based on the occasional interaction between autonomous actors retain more flexibility and enable addressing challenges at the level where they emerge. In other words, the organizational structure of energy

[1] Most of these causes are dealt with by the control mechanisms in place or redundant assets. Massive failures only tend to occur when accidents involve a multiplicity of interrelated causes, which in turn may create cascade effects (whereby small problems, affecting only a certain component, spread throughout the network).

infrastructures shapes the possibilities of actors to interact in order to coordinate for the operation of the system. Currently, researchers estimate that 80% of disasters in network industries have human or organizational causes and only 20% are caused by design or other factors (Roberts and Bea 2001, 179). Contemporary disaster and safety management literature hence incorporates the perspective that organizational reliability is just as crucial to the safety of technical systems as the reliability of the equipment. Hence infrastructure technologies should not be discussed in isolation but in relation to the organizational structure required to govern them.

The realization that the technical reliability of energy infrastructures has organizational requirements, however, is still accompanied by a lack of understanding concerning the concrete relationship between the technologies and organization of infrastructures and its effect on overall system performance or reliability. It is, for example, still unclear what "the characteristics of the institutions appropriate to a particular technology" are (Saviotti 2005, 25). What organizational structures would match the particular technologies or operational characteristics of current energy infrastructures and why? Moreover, a "thorough understanding of how networks of organizations operate and coordinate their actions to reliably operate complex, large scale technological systems is lacking" (De Bruijne 2006, 72). How can we know, for example, when the operation of energy systems requires central control or when it can be left to the autonomous entities? While our understanding of the technical and organizational dimensions of infrastructure reliability is well developed, the relationship between the two dimensions remains unclear. In turn, it seems that we lack the means to establish what organizational structures various energy infrastructures may require.

Overcoming the techno-organizational divide is of immediate practical relevance. Increasing fossil fuel scarcity and deteriorating environmental conditions urge for a transition towards a sustainable energy system. This implies moving from a fossil fuel based energy system to one based on renewable energy sources and carriers and supporting technologies; a development which is likely to affect the technical operation of energy systems and may even necessitate the building of new infrastructures. This in turn might require new organizational structures to ensure their reliable functioning. Decentralized solar photovoltaic (PV) electricity generation by households, for example, harbours the possibility of turning the electricity grid upside down. Consumers become producers, changing the role of distribution operators as one-way network companies into electricity hubs that deal with complex local electricity flows. In addition, the introduction of hydrogen as a motor fuel necessitates the use of liquid hydrogen trucks or the development of hydrogen pipelines for transportation, its own generation and storage facilities, not to mention the introduction of new fuel cell vehicles and fuel stations. Its operation may differ radically from the current petrol infrastructure. Of course, other examples pose less notable changes. Central wind and biomass generation, new geothermal and hydro power plants, or electric vehicles for instance may well involve new assets but are likely to be operated in similar ways as electricity and natural gas networks today. It also should not be forgotten that renewable energy technologies do not develop in a social vacuum. Their development is strongly related to developments in information technologies (IT), possibilities for distributed generation, and new roles for consumers. For example, the advent of smart metering opens up possibilities for decentral electricity and biogas generation, and allows for the measurement required to facilitate the feed-in of electricity produced by households. In addition, future systems tend to develop over prolonged periods of time with targets set far into the future, i.e. 2020, 2030 or even 2050. Hence a transition to a renewable energy system implies a series of technical changes that may or may not require changes in organization to ensure the reliability of technical operation.

In order to be prepared for these changes, the organizational requirements of reliability should be an important aspect in our thinking about and planning for future energy systems. Not only do we need to consider which technologies to use and how to introduce them, but also how they should be operated to ensure infrastructure reliability once they are in place. These concerns may seem rather premature, but developing energy systems without planning for their functioning seems rather careless in return. Yet this is exactly what is happening. Consider in this regard the visions and roadmaps that governments have developed to investigate future renewable energy systems and transitions thereunto. While the technical development and market deployment of new renewable energy sources and carriers plus supporting technologies and infrastructures have been thoroughly investigated, the organizational requirements for their reliable functioning have so far received little to no attention.[2] Plans for solar panels, wind farms, or biogas rarely focus on how they may alter the interaction among producers, transmission and distribution operators, retailers, and consumers. Technical roadmaps are not matched by, for example, complementary organizational roadmaps. Yet even when included, organization is rarely linked to reliability concerns. This is also because technical solutions are often sought at the expense of exploring organizational possibilities. Hence, there seems to be a discrepancy between the lessons on the relationship between organization and technologies in infrastructures and the way we currently plan the development of new renewable energy systems. So, the question becomes: what organizational structures may new renewable energy systems require and how to identify them?

1.1 Research Question, Objective, and Relevance

The point of departure in this research is that the technical reliability of energy infrastructures has organizational requirements, yet that these are difficult to determine and that the ability to do so is of great value in preparing for future renewable energy systems. In response, this research investigates:

[2] Scholars and policy makers have spent much effort trying to understand the role institutions play in the creation and diffusion of technologies and technical systems and the problems associated with lock-ins and path dependency (Nelson 1994; Perez 2001; Murmann 2003; Saviotti 2005). In response a wide repertoire of policies like subsidies, tax exemptions, etc. has been developed to overcome institutional barriers in the various stages of market introduction of technical innovations. No such repertoire of policies exists to support organizational changes. Only since liberalization and unbundling of the energy sector did scholars and policy makers become aware of the impact this might have on technical operation.

How to establish which organizational structures are required for the reliable operation of future renewable energy infrastructures?

The objective of this research project is to develop and illustrate a framework that pinpoints the organizational structures required for the reliable operation of future renewable energy infrastructures. It is essentially about *proposing* the means to find the organizational requirements of the technologies employed in future renewable energy systems in light of reliability. This makes the research methodological in nature; before any practical attempt can be made, a 'framework for alignment' needs to be established. Consequently, its purpose is to provide some general guidelines on how to approach the research question that may also serve as a rough manual for scientists and practitioners. The subsequent illustration of the framework at the hand of a possible transition to an infrastructure for the use of hydrogen as a motor fuel in the Netherlands should also be seen in this light; it explores the utilization, ability to generate accurate estimations, and practical relevance of the framework and contributes to its further refinement. This modest objective is representative of the explorative nature and early stages that research in this area finds itself in. Hence, by developing such a framework, this research also hopes to promote the systematic consideration of the organizational dimension of reliability in energy systems.

The development of the framework has added scientific value in furthering our understanding of the relationship between technologies and organizational structures in energy infrastructures, enhancing our ability to identify the organizational requirements of renewable energy technologies, and increasing our comprehension of the roles of various actors in maintaining reliability in socio-technical systems. The research also serves many practical purposes beyond the immediate for reliability, i.e. the ability to anticipate and prevent future network failures instead of responding to failures ex post. It allows scientists to enhance roadmaps to future renewable energy systems with an organizational dimension and stimulate awareness of possible organizational lock-ins and path-dependencies; it aids policy makers in overseeing the broader organizational implications of technical choices, helping them to make better informed decisions on facilitating socio-technical transitions; and it assists companies in sketching out their roles and responsibilities in future energy systems.

1.2 Research Design

The intention of this research is to utilize our understanding of reliability, socio-technical systems, and energy infrastructures to comprehend the relationship between the technological characteristics and organizational structures of energy systems in order to be able to approximate the organizational structures required for the reliable operation of future renewable energy systems. The core challenges in this regard are to capture the relationship under study and the complexity of the topic in a simple yet effective manner and to develop and illustrate a framework that is able to translate the technological characteristics of future renewable energy infrastructures into their organizational requirements. The execution of the research is split into three main parts, i.e. three sets of sub-questions. The first identifies the problem, introduces the main concepts, and presents our current state of conceptual and practical knowledge on the subject matter. The second part develops a framework for alignment and explores it on the petrol, natural gas, and electricity sectors in the Netherlands with the aim of further refining the framework itself. The final part introduces the case of a transition to the use of hydrogen as a motor fuel in the Netherlands and applies the framework to it in order to illustrate its utilization and relevance. The concluding chapter finally reflects in how far this research has succeeded in creating the desired framework and highlights possibilities for further research and practical applications.

Part 1

- What is (known about) the relationship between the technical and organizational dimension of energy infrastructures in light of reliability?
- What may a transition to renewable energy systems imply in terms of technical and organizational changes in energy infrastructures?

Part 2

- What organizational structures complement which technical characteristics of energy infrastructures in light of reliability and how to identify them?
- What are the organizational requirements of the petrol, natural gas, and electricity infrastructures in the Netherlands?

Part 3

- What does the transition to the use of hydrogen as a motor fuel in the Netherlands imply in terms of technical changes in energy and hydrogen infrastructures?
- What are the organizational requirements of hydrogen networks at various stages of their development?

The three sets of sub-questions differ greatly in the approach that is applied to address them. Let us therefore discuss how these sub-questions are investigated in more detail.

1.2.1 Understanding Reliability in Socio-Technical Systems

Finding the organizational requirements of the technical characteristics of energy infrastructures begins by understanding the concepts and their relationship, defining the problem, and providing expectations. This research does so through two avenues: by studying the existing scientific body of knowledge on the subject; and by addressing the transition to renewable energy in light of past energy transitions and their infrastructure implications. To this end, a literature research into theories on reliability, social-technical systems, and organization is undertaken on the one hand and on energy transitions and historical accounts of the development of energy infrastructures on the other.

The conceptual avenue starts by highlighting the organizational requirements of reliability, itself defined as the "the ability of [an energy] system to deliver the product (or service) transported over the network without interruption and without deterioration of its quality" (CPB 2004, 18), i.e. the "ability to supply the quantity and quality of energy desired by the customer when it is needed" (McCarthy et al. 2007, 2153). It then notes the lack of understanding surrounding the exact relationship between technical operations and organization in ensuring reliability and the disability to determine what organizational structures are required for particular energy infrastructures. It suggests proceeding by investigating energy infrastructures as socio-technical systems, in which technical and social factors are heavily interwoven and together account for system performance, and addressing the implications of that perspective for maintaining reliability.

In the technical dimension of socio-technical systems, focus goes to the assets or artifacts that make up the supply chain of an energy infrastructure, i.e. the tangible objects involved in the operation of an energy system such as pipelines, wires, pressure stations, generation plants, control systems etc. Reliable operation of these technologies depends on their proper functioning, regular maintenance, and timely replacement. Frequently, accidents in infrastructures occur when one of them fails to perform adequately for reasons of damage, old age, misuse, or natural disasters. Just as important for system functioning, however, is that these technologies operate in a complementary fashion. For energy infrastructures to deliver energy from production facilities to consumers requires all supply chain components, such as sources, generation, trade, transmission, storage, distribution, metering, retail, consumption, and regulation, to work together.

In the social dimension of socio-technical systems, attention goes to the interaction between infrastructures entities[3] (based on the above-mentioned supply chain components) and the wider institutional environment in which they operate (Weijnen and Bouwmans 2006; Hughes 1983; Ewertsson and Ingelstam 2004; Nightingale et al. 2003). After all, the management of daily operations occurs at the hand of individuals and companies. Special attention goes to organizational structures, i.e. the "context and forms of coordinative structures" among entities (De Bruijne 2006, 74), that co-determine the possibilities of entities to collaboratively operate infrastructures and ensure reliability. Two aspects play an important role in this respect: what are the responsibilities of entities (who does what, when, and how) and what is the nature of their interaction (hierarchical or horizontal coordination)?[4] Typically, organizational structures are distinguished based on the degree of vertical integration involved (Williamson 1975, 1979; Harrigan 1984; Provan and Kenis 2007). In this research, four ideal-types particularly attuned to technical operations are

[3] We prefer to use the term 'entities' over 'actors' or 'organizations' because we are dealing with them as nodes and links in a technical system, each of which has to perform their task in order for the overall system to function. We do not see them as actors with autonomous interests, i.e. as having economic preferences that may be contrary to reliability considerations. Such considerations should not be part of an exercise to find the organizational requirements of the technical functioning of renewable energy systems.

[4] In economic literature, a third variable is often present: whether actors are public or private.

distinguished: 'vertical integration', 'lead entity', 'common operation', and 'incidental coordination'.[5]

Finally, reliability is conceptualized within this socio-technical context. Key is the notion that there needs to be a certain degree of coherence between the technical and organizational dimensions to ensure infrastructure performance (Finger, Künneke, and Groenewegen 2005-2010). As such, it is hypothesized that reliability is best ensured when technical assets are properly maintained and supported by an organizational structure that facilitates their complementary operation. It is noted in this respect that centrally and decentrally operated networks seem to match more or less vertically integrated forms of organization among entities. However, the major challenge of this research is also re-emphasized: while our understanding of the technical and organizational dimensions of energy infrastructures and reliability is well-developed, the exact relationship between the organizational requirements that technologies have and the operational possibilities that different organizational structures offer remains unclear. In turn, it seems that we lack the means to establish what organizational structures future renewable energy infrastructures may require in light of reliability.

The practical avenue starts by positioning the transition to renewable energy systems as a specific challenge for the maintenance of reliability in energy infrastructures; it implies a series of technical changes in infrastructure systems whose reliability requires a degree of coherence between its organization and operation. It defines the transition to sustainability as the process of moving from a fossil fuel based energy system to one based on renewable energy sources and carriers and supporting technologies (Criekemans 2011; IEA 2009; UCP 2010). It then points to the sheer number of possible ways in which these renewable energy technologies may affect network operations of existing and new infrastructures. The question becomes which organizational structures are required to restore the necessary degree of coherence to ensure reliable operations. This brings us back to the research question and highlights the perspective of this research: how to align network organization to technical changes (and not vice versa).

Attention then turns to analyzing the body of literature on the effects of the introduction of new energy sources and carriers on infrastructure development in order to have some expectations regarding the technical and organizational changes

[5] In 'vertical integration' infrastructures are organized by a single entity that coordinates all upstream and downstream technical operations from production to transmission, distribution, and retail in a top-down fashion from a central control center. In 'lead entity' several entities have formal responsibility for their part of technical operations but where a single entity (frequently the transmission system operator) acts as a lead organization for key coordination activities. 'Common operation' is a more decentral structure of organization that represents the situation in which each entity is essentially autonomous in executing their technical responsibilities, but in which groups of entities may share the responsibility / have to coordinate for certain control mechanisms while none of the entities has central authority. 'Incidental coordination' is a strongly decentral organizational structure in which entities coordinate only when occasionally required and in such a way that bilateral interaction between the relevant entities is usually sufficient.

we are likely to encounter in the upcoming transition. Literature studied includes past energy transitions and transition theory (Dunn 2002; Grübler 1990; Grübler and Nakicenovic 1991; Geels 2002 and 2004; Shackley and Green 2007), infrastructure development according to the literature on large technical systems (LTS) (Hughes 1983; Jackson et al. 2007; Ewertsson and Ingelstam 2004; Sawhney 2003), and historical accounts of infrastructure organization and governance (De Bruijne 2006; Verbong and van der Vleuten 2004; Millward 2004; Nightingale et al. 2003). While none of the fields provide the exact information sought, all of them cover certain aspects; and while the fields write from their own perspective, there are nonetheless largely overlapping and related. A number of heuristics are distilled from the overview that allow us to form some expectations as to what to expect from a transition to renewable energy and its possible infrastructural consequences.

1.2.2 Bridging the Techno-Organizational Divide

The second part addresses the core challenge in this research: how to express technological characteristics in terms of their organizational requirements. This is done in two stages. First, we develop a framework that presents a stepwise progression from technical characteristics of energy infrastructures to organizational structures. Second, we explore this framework on the contemporary energy vectors of petrol, natural gas, and electricity to gather feedback for refining the framework.

For the development of a framework for alignment, the immediate question is where to start looking for answers. Fortunately, the definitions of technology and organization already point to a number of matters to consider. First of all, regarding the technology, we are interested in finding those aspects of technical operation that involve human interaction - not mere artifacts or assets as such, but functions that ensure the complementarity among infrastructure entities.[6] A convenient starting point is given by Finger et al. (2006) who distinguish four technical functions that can be considered critical for safeguarding the technical complementarity of infrastructures: interoperability, interconnection, capacity management, and system management.[7] The question then becomes what operational concerns a renewable

[6] While the functioning of assets is a purely technical issue, remaining limited to one chain component (for example, exchanging one pressure station by another might not affect the coordination among network operators), technical functions focus on how varying assets work together and hence may involve coordination among supply chain entities.

[7] Interoperability focuses on the "mutual interactions between network elements" (Finger et al. 2006, 11-12) such as the complementarity between energy sources/carriers and delivery systems, like voltage levels and electricity wires, or energy characteristics and application requirements, like natural gas quality and domestic boilers. Interconnection deals with the "physical linkages of different networks that perform similar or complementary tasks" (Finger et al. 2006, 11-12). This includes facilitating the connection between local distribution and national and continental transmission networks and planning for system additions. Capacity management concerns the allocation of "scarce network capacity to certain users or appliances" (Finger et al. 2006, 11-12). Issues pertain to the operational balancing, unit commitment and capacity utilization, maintenance scheduling, and the long-term planning of network and production capacity (Künneke and Finger 2007, 310-311). Finally, system

energy system might have with regard to these technical functions. This not only paves the way from technology to organization, but also helps us to focus on a few key variables, i.e. relevant operational tasks for entities in an energy infrastructure, instead of the multitude of technologies involved.

Secondly, two key aspects of organization need to be identified if we wish to come to organizational structures: the amount and responsibilities of entities involved in technical operation and the nature of their interaction (hierarchical or horizontal). Regarding the former, the question is which entities are involved in the facilitation of a particular critical technical function and to what degree. This allocation of responsibility draws upon contemporary practical experiences in energy infrastructures as a helpful reference point, utilizes the infrastructure supply chain entities (sources, generation, trade, transmission, storage, distribution, metering, retail, consumption, and regulation) as possible categories, and classifies their degree of involvement from none to indirect, supportive, weak direct, strong direct, and leading involvement. Combined, a picture emerges that shows which entities do what, when, and how, and which entities play a key role per critical technical function. The latter looks at the stringency of the coordination requirements of critical technical functions. Is central top-down coordination necessary or may operational control be left to autonomous entities? To address this question, we investigate an interesting proposition by Künneke et al. (2008) to relate infrastructure technologies to their coordination requirements. In their article they relate transactional characteristics (from transaction cost theory) to the control mechanisms required to facilitate critical technical functions. These characteristics can in turn be linked to degrees of central coordination, i.e. more or less vertically integrated forms of organization. In addition, literature on accidents in large socio-technical systems points to a number of infrastructural and situational features that may affect the need for and operation of control mechanisms and hence coordination requirements. Combined, six degrees of centralized coordination are distinguished between autonomous entities that may act without coordination and the need for a central coordinating center that dictates and supervises.

Finally, the results of the two key aspects of organization need to be brought together in order to generate the overall organizational structure required. Whereas step 2 provides us with an idea of which entities are involved in the facilitation of a particular technical function, step 3 sheds light on the coordination requirements among the involved entities for that function. Two questions remain however. First, which combination leads to what organizational structure? While no straightforward answer exists, the literature on types of actor networks (Provan and Kenis 2007) and vertical integration (Williamson 1979, Harrigan 1984; Perry 1989) gives us some ideas how to relate the outcomes of step 2 and 3 to a few ideal-type organizational structures (vertical integration, lead entity, common operation, and incidental

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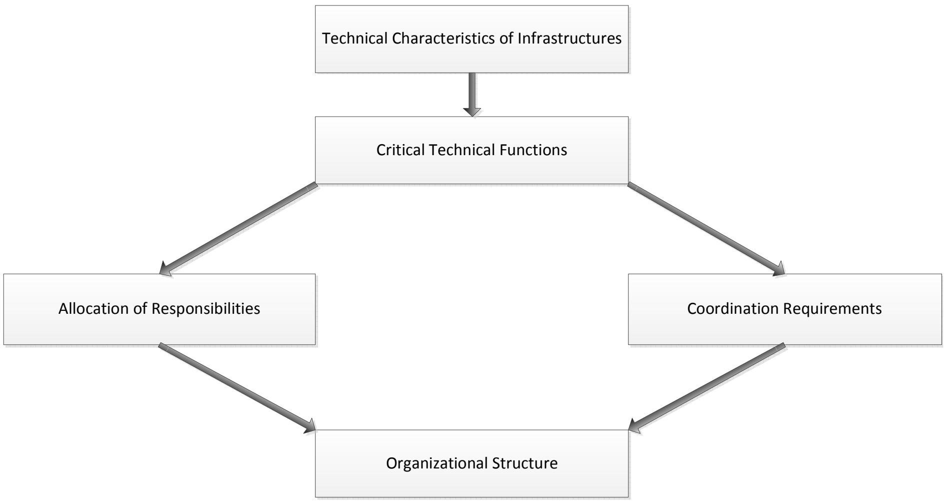
management "pertains to the question of how the overall system (e.g. the flow between the various nodes and links) is being managed and how the quality of service is safeguarded" (Finger et al. 2006, 11-12). This entails mostly aligning production with consumption and ensuring that the energy system is able to adapt to changing conditions.

coordination).[8] Second, how to combine the outcome for each technical function into one whole? While steps 2 and 3 present detailed answers per technical function, for an overall structure we need to somehow responsibly generalize the aggregate. To this end, the results thus far are reinterpreted on the level of the overall infrastructure.

Building on these considerations, a framework for alignment is proposed (and operationalized) along four subsequent steps:

Figure 1.1 A framework for alignment



After a framework has been set up, it is time to explore its utilization and capability to produce accurate estimations. Three cases 'test' the framework, give practical examples, and allow us to concretize and refine core concepts before applying it to the hydrogen case: the petrol, natural gas and electricity sector in the Netherlands. Several reasons account for this. First, electricity, natural gas and petrol are the three main energy vectors in modern economies (and are likely to be familiar to the audience). Second, they allow for a possibility to reflect the results against contemporary sector organization and reliability levels. Of course, one could argue that it might be better to

[8] Basically, if centralized coordination is required for a technical function and a single entity stands out as the most responsible, then the structure of a lead entity seems fitting. If, however, centralized coordination is required but many entities are roughly equally involved, then vertical integration seems best suited. Next, if criticality is low and a single entity is responsible for that particular technical function, a completely decentralized structure seems fitting as coordination is likely to be only occasionally required (if at all). Finally, the combination of low criticality and multiple entities that are equally involved seems to be best facilitated through common operation in a decentralized setting. Of course, this is very black and white, but it nevertheless presents a guiding reasoning or reasoned yardstick.

use current renewable energy systems as explorative cases. This is partly true. Iceland's hydrogen bus system might be very illustrative in this regard for example. Yet such a focus does not reflect the scale in which a transition to sustainability is generally implemented in countries nor is it desirable to explore the framework on fledgling energy industries that themselves might lack appropriate organizational structures. Doing so would not achieve an accurate comparison of the results with practical operation and reliability levels. Third, by focusing on the Netherlands for the three explorative cases and the illustrative hydrogen case (discussed below), a certain continuity between the petrol and hydrogen sector is achieved which allows us to map the changes in organization from 2010 until 2050.[9] In any case, it is more important to explore the framework on a variety of sectors rather than a host of countries, considering we are looking for technical and not cultural operational requirements.

The application of the framework proceeds by executing the four steps described after the technological characteristics and general operation of the three energy vectors have been introduced. A technical understanding of the three sectors is required for framework application. The information is gathered through a literature study on the Dutch energy vectors (IEA 2009; NNEN 2010). As we will see, the three sectors differ in their technical operation and required organization, the latter of which also differs in varying degrees from those found in practice, making for an interesting comparison.[10] In addition, the three cases identify a number of important considerations regarding infrastructure and situational features that need to be taken into account while applying the framework.[11]

1.2.3 Framework Illustration: The Case of Hydrogen

In the third part, the framework is applied to a transition to the use of hydrogen as a motor fuel in the Netherlands. Throughout the last decade, the Dutch government has repeatedly stated its intention to make a transition towards a more sustainable energy system (NMP4 2000). Consequently, a plethora of new renewable energy technologies are developing under its energy transition framework as well as under 'regular' energy policy. One possibility in particular, a transition to the use of hydrogen as a motor fuel as developed by the Energy research Centre of the Netherlands (ECN) for the European Union's (EU) HyWays project, presents an interesting and challenging case for framework exploration because it envisions the build-up and use of a variety of hydrogen technologies and networks between 2010 and 2050. The

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[9] The choice of the three explorative cases followed that of the illustrative hydrogen case. Only the hydrogen case truly illustrates the model as it is intended for use on future renewable energy systems.

[10] A comparison between the results found by the framework and existing organizational structures of the three sectors in the Netherlands also reveals some new insights into the debate on the effects of unbundling on sector operation and reliability.

[11] The considerations do not affect the four steps as such, nor represent additional technical functions for that matter, but are best described as infrastructural features and situational features that affect the parameters of the functions and their facilitation (in terms of speed and scope) and hence influence their coordination requirements.

hydrogen case study serves to illustrate the use of the framework, concretize concepts by applying them (stimulating further refinement), and to show the usefulness of the framework for practical purposes.

The hydrogen energy system has been selected because it fulfills two important conditions. First, it involves the introduction of a new renewable energy source or carrier (and supporting technologies) that may require the restructuring of energy infrastructures and their organization. Second, the case involves new energy technologies whose possibilities for physical networks are sufficiently known; otherwise the framework for alignment cannot be applied. In addition, the transition to hydrogen is chosen for two very specific reasons. First, so far hardly anyone has explored how a hydrogen network should be organized at various stages of its development from a reliability point of view. This gives us the unique opportunity to explore the framework for alignment without having a bias towards certain organizational structures.[12] Second, and perhaps more importantly, a transition to hydrogen can be considered one of the most interesting cases. As we will see, it implies the presence of three different networks (on-site production, truck distribution, and pipelines) in varying degrees at various points in time. Such large network changes are likely to require very different organizational structures. This diversity might make hydrogen a challenging example to explore the framework on, but it may also more accurately reveal the obstacles one encounters while applying it. Of course, if the framework proves satisfactory on such a demanding case, its value increases.

The choice for the Netherlands stems first and foremost from the familiarity of the author with the country. If we are to investigate something as uncertain as future energy systems, it seemed prudent to at least situate it in a familiar setting. Secondly, this research became part of the Energy Delta Gas Research project (EDGaR) during its execution. This national consortium of GasUnie, Kiwa, Enexis, Liander, Stedin, GasTerra, Groningen University, Delft University of Technology, Energy research Center of the Netherlands, and the Hanze University Groningen conducts a strategic research program on gas and sustainability with the aim of developing the knowledge and technology needed for the Netherlands to evolve from its strong position in natural gas to a sustainable energy mix. The choice for the Netherlands as country of choice hence arose from this program. Moreover, as stated above, it is not the country that matters per se; it is about the organizational requirements of the technical operation of a renewable energy infrastructure, without the cultural, economic, political, or social baggage attached.

The choice to illustrate the framework by means of a case study can be simply explained. Case studies are a preferred strategy in social science research when 'how' and 'why' questions are posed. Due to the exploratory nature of the proposed case study, the definition we intend to follow deviates from the general notion that case

[12] Of course we should not be blind to how existing hydrogen networks, like in Iceland, are organized. It needs to be noted however that such comparisons are hazardous. Contemporary examples would not necessarily encounter the scale of hydrogen networks envisioned for 2050 in the Netherlands.

studies are especially helpful when the researcher has little control over events and when the focus is on a contemporary phenomenon within some real-life context (Yin 2003). As this does not suit hypothetical future phenomena such as a transition to hydrogen, we propose to follow the definition of Van der Vleuten, Westerheijden and 't Hart: "A case study consists out of a description of 1 or a few cases that can be considered to be concrete examples of certain general mechanisms" (Van der Vleuten 2001, 75). In this respect, the case of a transition to hydrogen is seen as a concrete example of the development of a renewable energy source or carrier and supporting technologies and infrastructures (one might of course just as well choose solar or wind energy). Naturally, such case studies "are limited in their generalizability, creating the danger that results are time, sector, country and technology specific. However, when they are used to contextualize key points of an explanation, and the explanation, and not the cases, carries the argument, case-studies can be very powerful" (Nightingale 2003, 479). The hope is that the exploratory case study leads to support for research premises and hypotheses plus refined variables and measurement tools. The value of this perspective also lies in the fact that it views the researcher as the one determining what does and what does not belong to the context of the researched phenomenon. This helps us to deal with the complexity of the problem by tuning the case of a transition to hydrogen to the needs of adequately illustrating the framework for alignment. It allows us for example to focus on personal transport applications of hydrogen only, neglecting stationary applications, and setting the timeframe until 2050. This way, the case is better suited to what the most likely hydrogen applications in the Netherlands are considered to be and allows for enough time to realize a satisfactory introduction of hydrogen so as to assess a sufficient part of a transition. More importantly, focusing on hydrogen as a motor fuel only allows us to limit the case to a single infrastructure, whereas including the use of hydrogen in buildings might convolute the picture. Though an interesting consideration for policy makers and infrastructure entities, it serves no purpose to include buildings if the aim is to illustrate the framework in the clearest manner possible.

The illustration of the framework on the hydrogen case basically involves introducing the HyWays roadmap that stipulates which hydrogen technologies and networks are foreseen to be in place at various stages of a transition in the Netherlands and then executing the four steps described in the previous section on it. This will be done in two separate chapters. The first introduces the case of an energy transition in the Netherlands, the various hydrogen supply chain technologies and networks that are considered in this regard (and that are deemed most realistic in light of Dutch energy expertise and national characteristics), and then presents the HyWays roadmap, i.e. three snapshots of how a hydrogen infrastructure would look like in 2020, 2035 and 2050.[13] Working with static images or snapshots is a prerequisite for framework

[13] The timing of the three snapshots deviates from that of the HyWays roadmap, which discusses 2010, 2030, and 2050. This alteration was chosen in light of more recent insights regarding a hydrogen uptake in the Netherlands. The hydrogen technologies and the nature of the networks in the snapshots, however, have remained the same. In short, all the technical changes remain the same; they have merely been put later in time.

application considering its static comparative nature. As we will see, the hydrogen delivery network changes quite radically throughout the stages of development from localized and small-scale onsite production supported by truck delivery to a national pipeline network. After this presentation of the technical side of a transition to hydrogen, the framework's four steps can be applied to each of the three snapshots to find the complementary organizational structures for that moment in time. Combining the results of the three snapshots an organizational roadmap is created that complements the technical HyWays roadmap.

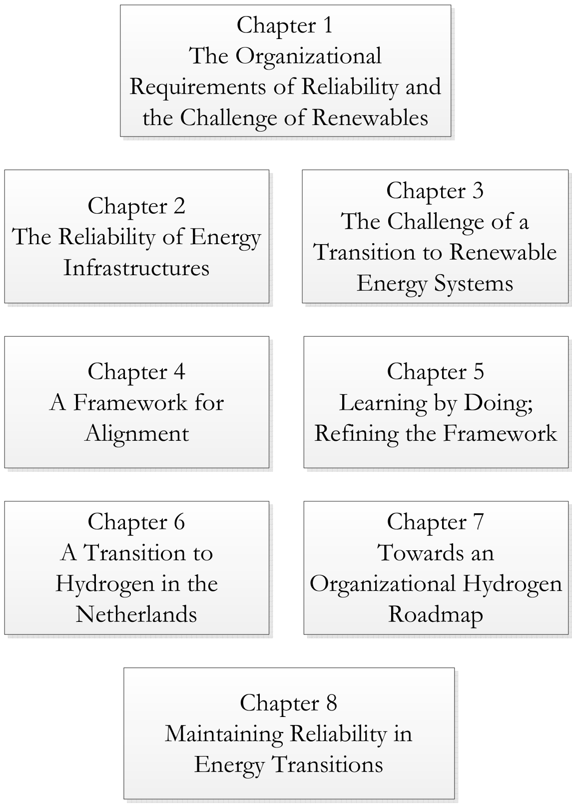
Once established, it is interesting to explore the implications of the organizational roadmap. How do the roles and responsibilities of infrastructure entities, such as transmission and distribution system operators, hydrogen producers, and retailers, change throughout the roadmap? In addition, how might policy makers pursue a co-development of the technical and organizational dimensions of the roadmap? Moreover, how might the inclusion of organizational alignment during the execution of a technical roadmap influence the process and progress of the overall roadmap? Would organizational path-dependencies and lock-ins call for a different outcome to be preferable and more feasible? How might sector incumbents respond to reliability-induced organizational changes? This will be done in the concluding chapter.

As a final comment, we would like to state that it should be apparent that the hydrogen case study is not for everybody. Those interested in finding which future alternative for oil as a motor fuel is likely to emerge, or which hydrogen technology (on-site, pipelines, trucks) is the 'best' or most likely option are not going to find any answers here. We are not attempting to predict the future in terms of what the new dominant energy technology is going to be. The research is also not about what policies (and instruments) should be used to stimulate the development and deployment of hydrogen technologies. Sufficient research already exists in that regard. In addition, this research does not aim to design organizational structures of hydrogen networks in light of economic, social, or other criteria than reliability. For an interesting work on a market design for reliable electricity supply see Knops 2008. Finally, this research does not study the presence of co-evolution of institutions and technologies in the development of hydrogen in the Netherlands to date. The goal is merely to identify the necessary organizational structures that would ensure the technical functioning of hydrogen networks. In this respect, scholars interested in hydrogen might benefit from this research because it attempts to identify the organizational requirements for the reliable operation of future hydrogen networks.

1.3 Structure of the Research

The chapters of this research are structured along the three main parts, i.e. the three sets of sub-questions. The second and third chapter present our current conceptual and practical understanding regarding the relationship between organizational structures and technical characteristics of energy systems respectively and address the research problem and main concepts in greater detail. Afterwards, the framework for alignment is proposed in the fourth chapter and its four steps are explored on the petrol, natural gas, and electricity sectors in the Netherlands in the fifth chapter. Next, chapter six introduces the case of a transition to the use of hydrogen as a motor fuel in the Netherlands while chapter seven applies the framework to it in order to illustrate its utilization and relevance. The concluding chapter finally reflects upon the framework developed in light of the research question and objective stated in this introductory chapter and explores the implications of the findings for various purposes, i.e. for scientists, policy makers, industry incumbents, or other companies.

Figure 1.2 Structure of the research



Part I

2. The Reliability of Energy Infrastructures

The point of departure in this research is that the technical reliability of energy infrastructures has organizational requirements, yet that these are difficult to determine and that the ability to do so is of great value in preparing for future renewable energy systems. This chapter conceptualizes the concept of reliability in a socio-technical environment and leaves the specific challenges posed by the transition to sustainable energy sources and carriers to the next chapter. It asks what is known about the relationship between the technical and organizational dimension of energy infrastructures. Hence, it presents the conceptual problem setting, defines the core concepts of this research and elaborates upon their relationship, gives background information, and lays the foundations for a framework for alignment. It does so by first defining the concept of reliability in energy infrastructures and highlighting that their technical functioning has organizational requirements. To better understand what this implies for maintaining reliability, the perception of energy infrastructures as socio-technical systems whose performance requires a certain degree of coherence between its technical and organizational dimension, is elaborated. Finally, these insights are used to highlight our lack of ability to relate technological characteristics of energy infrastructures to their complementary organizational structures in light of reliability.

2.1 The Organizational Requirements of Reliability

For energy infrastructures, reliability "reflects the ability of the system to deliver the product (or service) transported over the network without interruption and without deterioration of its quality" (CPB 2004, 18), i.e. can be broadly described as "the ability to supply the quantity and quality of energy desired by the customer when it is needed" (McCarthy et al. 2007, 2153) or the ability to maintain and execute error-free operations (Shrivastava et al. 2009, 1363).[14] In electricity, for example, reliability concerns interruptions and fluctuations in voltage. For natural gas, the quality and composition of the gas can be added to this list. Reliability should not be confused with 'security of supply'. "While the term 'reliability' relates to the quality of the network, the concept of 'security of supply' is more general and refers to the long-run provision of network goods and services. The main difference between reliability and security of supply is that the latter concept also includes sufficient supply of the commodity transported over the network. In other words, in contrast to reliability, security of supply also includes potential crises on the supply side" (CPB 2004, 18-19).[15] For example, typical concerns of reliability include a lack of network capacity

[14] To engineers, reliability is a key attribute of the quality of a product and is defined as "the probability that an item will perform a required function without failure under stated conditions for a stated period of time" (Landau and Chisholm 1995, 72).

[15] Others also recognize this difference, but configure the pieces slightly differently. McCarthy et al. (2007, 2153), for example, distinguish two dimensions of reliability when they analyze the electricity sector: adequacy and security. To them, "adequacy refers to the ability of the system to supply customer requirements under normal operating conditions. It considers the system

(utilization, intermittency), flexibility (demand fluctuations, equipment outages, expandability), a lack of maintenance or operating expenses, failures caused by users or network parties (repair), and failures caused by mismatches of supply and demand (CPB 2004, 19; McCarthy 2007, 2153-2158). Common security of supply challenges are geopolitical tensions with oil and gas producing countries, market price fluctuations, and other external events, such as natural disasters that damage infrastructures. It is important to note that this research deals solely with the reliability of energy infrastructures, i.e. the adequate operation of the technologies involved in the infrastructure. In other words, it focuses on preventing technical and operational failures, not on political, economic or environmental threats to system functioning.

The concept of reliability in energy infrastructures has changed considerably over the last decades. Until the mid-1990s, most energy infrastructures were operated as public monopolies in which supply chains were fully integrated vertically, because the transportation and distribution networks of energy infrastructures were considered to have the characteristics of a natural monopoly. Governments, both through ownership and regulation, controlled infrastructure planning, construction and service performance, like universal provision, by means of central planning and allocation of funds (Weijnen and Bouwmans 2006, 128). In this setting, engineers and "disaster and reliability experts focused mainly on the reliability of technologies" (De Bruijne 2006, 52) and the direct causes of accidents such as failing equipment. Latent causes of accidents were often neglected while operator error or technical failures were frequently considered, "if only because the far more subtle ways in which these factors caused accidents went largely unnoticed" (De Bruijne 2006, 52).[16] Put differently, energy infrastructures were characterized by an engineering culture in which reliability was considered an issue of the functioning of technical assets (Weijnen and Bouwmans 2006, 127).

This governance structure of infrastructures was dramatically altered in the last two decades however. Liberalization, privatization and deregulation meant the unbundling of vertically integrated infrastructures into competitive and public segments of the value chain, whereby energy production and service provision were left to market forces and the network components, with their natural monopolistic characteristics, remained in government hands (Midttun 2001, Newbery 1997, 1999). In the process, the complexity of the social network, i.e. the amount and variety of

statically. Security includes the dynamic response of the system to unexpected interruptions, and relates its ability to endure them." In addition, Jonker (2010, 43) states that "Adequacy is a measure of the ability of the power system to supply the aggregate electric power and energy requirements of the customer within component ratings and voltage limits, taking into account planned and unplanned outages of system components. Security is a measure of power system ability to withstand sudden disturbances such as electric short circuits or unanticipated losses of system components or load conditions together with operating constraints."

[16] Roberts and Bea (2001, 179) state in this regard that when "a catastrophic error occurs and an investigation is conducted, it usually focuses first on the engineering design and manufacturing components of the incident. […] The investigation usually ends here, but this is almost never the whole story, because individual acts are embedded in systems that direct the individual's behavior."

actors (Amin 2000), has increased as a consequence of new actors, also often in new roles, entering the playing field. In turn, "the options to steer the development of the technical infrastructure have changed in nature" (Weijnen and Bouwmans 2006, 128). Previously, government policy makers could directly interfere in the planning of the physical system. Now, "investment signals (whether for the purpose of innovation or capacity expansion) are […] established through market forces" (Weijnen and Bouwmans 2006, 128). In response, the understanding of reliability changed. It became increasingly clear that while accidents were actively or directly caused by technical failures and/or human error, they often had more fundamental or latent causes hidden in design, management, and organization (Turner 1976; Shrivastava et al. 1988; Reason 1990, 1997; Weick 1993; Grabowski and Roberts 1996; Pidgeon 1997; CAIB 2003; De Bruijne 2006). This was especially the case with massive failures where small accidents were able to cascade throughout the system due to poor communication and coordination among the various actors operating it and the overlapping responsibilities and different priorities of actors. Perrow goes a step further stating that "as long as technology and organization are independently created and viewed as distinct issues, their constant interdependence in real life will remain a source of hazard" (Bourrier 2005, 99). Not surprisingly, from the 1980s onward, special attention turned to "the effects of the organizational environment on reliability issues and disasters" (De Bruijne 2006, 52), most notably the people and organizations operating complex systems. It appeared that "organizational reliability is just as crucial to the safety of a technology as is the reliability of the equipment" (Pool 1997, 250). In other words, the technical reliability of energy infrastructures has organizational requirements.

De Bruijne (2006, 74-76) points out a number of factors that have made the reliable operation of infrastructures more difficult. First, actors in the liberalized and privatized setting have increased in numbers and may pursue their own interests. This may produce behavior that is in conflict with system reliability. Second, infrastructure operators have lost ownership over "vital infrastructure elements as a result of restructuring, and more importantly, over what is transported across the infrastructures." This creates information asymmetry and demands continuous coordination and communication to overcome. Third, "as responsibility for reliability is distributed under competitive conditions in networks of [actors], social shirking may occur." Fourth, reliability is an ongoing accomplishment in at least two ways. On the one hand, reliability management problems may change over time as infrastructures develop technically and grow in scope and complexity. Challenges to reliability must be continuously reassessed and readdressed. On the other hand, operational problems "can migrate within a network of organizations [, i.e.] addressing a problem in one part of the network may create (un)intended consequences in another part of the network." Managing such cascading or migrating effects becomes increasingly difficult among a growing number of actors.[17]

[17] As was already noted, before liberalization and unbundling the network was highly integrated vertically, while we currently know unbundled companies for production and transmission and distribution. This has led to a whole debate on the state of infrastructure reliability. On the one hand, the critics of infrastructure reorganization state that whereas

The realization that the technical reliability of energy infrastructures has organizational requirements, however, is still accompanied by a lack of understanding concerning the concrete relationship between the technologies and organization of infrastructures and its effect on overall system performance or reliability. It is, for example, still unclear what "the characteristics of the institutions appropriate to a particular technology" are (Saviotti 2005, 25). Nelson (1994, 61) similarly noted with regard to the co-evolution of institutions and technologies that it is not yet clear how various institutions can be represented so as to compare them to technologies. What organizational structures would match the particular technologies or operational characteristics of current energy infrastructures; and why? Only a handful of studies (Starbuck and Milliken 1988; Weick 1990; Shrivastava 1992) have related issues of reliability and sector organization. Yet, those that do "[m]ade no effort to address linkages among organizations" or network actors (Roberts 1994, 3), instead focusing on reliability within a single firm. As such, they become largely irrelevant for the organization or management of large-scale energy infrastructures that consist of multiple actors and which "[a]re linked with one another in different [technical] ways from those posed by institutional theory, agency theory, transaction cost economics, resource dependency theory, or the networking approach" (Roberts 1994, 3). Moreover, the literature on infrastructure organization and reliability often misses technical aspects, despite a rather technology oriented view of reliability, focusing instead on the effect of changes in organizational structures on reliability levels (De Bruijne 2006). Similarly, while scholars on the co-evolution between institutions and technologies have developed a thorough understanding of both concepts and acknowledged the existence of a strong relationship and mutual influence between organizational structures and technical functioning relatively early on (Nelson 1994, Nelson and Winter 1982, Murmann

markets might be more efficient for matching supply and demand and decreasing energy production costs, the unbundling of the vertically integrated structure has increased the complexity and need to coordinate (Quiggin 2002; De Bruijne 2006, 4), while the increasing number and variety of actors (each with their own goals and objectives) in the system complicates "the matter of reliable and safe operation of the infrastructures" (Herder and Thissen 2003, 3). Accordingly some worry that "our ability to manage a technology, rather than our ability to conceive and build it, may become the limiting factor in many cases" (Pool 1997, 276). They point to the California electricity blackouts and other recent failures to back up their claims. Others, however, are more optimistic about reliability in the liberalized setting, pointing to "a pretty good track record with regard to issues of safety and reliability" They claim that overall restructured infrastructures "did not experience large-scale disasters, nor was the provision of services severely disrupted" (De Bruijne 2006, 5). Unfortunately, no clear answer exists. On the one hand, there exists no single index or uniformly accepted reliability performance data, making comparison difficult. On the other hand, the findings that do exist can be used to support both sides of the debate. As such, the effects of restructuring on the reliability of infrastructure services remain unclear (De Bruijne 2006, 399). In the face of a lack of answers, the prevailing consensus seems to be that while reliability performance remains about equal, the efforts of coordination among actors have increased to achieve those same levels. Perhaps the most relevant lesson is that the debate itself again shows the importance of adequate organization for the reliability of infrastructures.

2003, Perez 2001, von Tunzelmann 2003), they still struggle to establish the mechanisms through which both dimensions affect each other. They also miss a direct connection to the concept of reliability. As a consequence, there is no framework with which to understand how networks of actors coordinate their actions to reliably operate energy infrastructures (De Bruijne 2006, 72). Because such a framework is missing, "we do not have a vocabulary for discussing systems in organizational research, conceptual notions about the kinds of systems that can and cannot work, or advice to give managers who must operate in systems of organizations" (Roberts 1994, 8-9). In turn, scholars lack the means to establish what organizational structures may be required by energy infrastructures. If we wish to understand the organizational requirements of future renewable energy systems, however, this is exactly what needs to be set up.[18] Hope comes from the field of science and technology studies on socio-technical systems and literature on the co-evolution of and coherence between technology and institutions. Let us therefore discuss these concepts, starting by elaborating upon energy infrastructures as socio-technical systems and afterwards addressing the implications of that perspective for maintaining reliability.

2.2 Energy Infrastructures as Socio-Technical Systems

Defining the concept of energy is markedly easier than that of infrastructures. Energy refers to the energy sources, e.g. fossil fuels (coal, oil, gas), renewables (solar, wind, hydro, geothermal, tidal, waste, and biomass), and alternative energy sources (nuclear), and energy carriers, such as electricity or hydrogen. Currently, the three dominant energy vectors in most modern economies are oil, natural gas and electricity, which are used for a variety of industrial, household or transport purposes. Their infrastructures are both heavily interconnected as well as separated. Oil and gas may, for example, both be used to generate electricity, but each has its own transportation network. In the future, more use of renewable and alternative sources is expected.

A proper definition of infrastructures or network industries, in contrast, appears difficult to find. Despite the fact that literature on infrastructures has received increasing attention over the last decades, "no clear definition of the term 'network industry' has really crystallised" (TILEC 2003). The problem is that most industries involve a network of some sorts, making it difficult to distinguish infrastructures from other industries, or that the focus in the definition is solely on the physical network, neglecting the industries. In addition, other definitions seem to focus on the physical over the operational dimension involved in infrastructures. For example, Finger et al. (2006, 4-5) characterize infrastructures as "physical networks that link various industries along the supply chain with each other and with consumers." Perhaps a good summary of the situation is therefore made by Weijnen and Bouwmans (2006, 124) who state that "the notion of 'infrastructures' generally refers only to the physical

[18] A similar plea was made by Grabowski and Roberts (1996, 3) who wrote that large-scale systems such as infrastructures are "poorly understood, particularly with respect to the interactions of their components, and with respect to the impacts of those interactions on the error propensity of the system", and that understanding the characteristics of these systems could assist in designing and developing reliable infrastructures.

network that connects suppliers and end users of an infrastructure-bound service [but that an infrastructure system should include besides the transport and distribution network] the carriers, conversion, and storage facilities, as well as the governance, management, and control systems that are needed to make the system meet its functional specifications and its social objectives." Similarly, the US Critical Infrastructure Assurance Office (CIAO) defined infrastructures as "the framework of interdependent networks and systems comprising identifiable industries, institutions (including people and procedures), and distribution capabilities that provide a reliable flow of products and services […]" (Rinaldi et al. 2001, 13). Considering that none of these descriptions are a sharp definition, although they do describe well what should be included in the concept of infrastructure, let us continue by approaching energy infrastructures as socio-technical systems to clarify the concept of infrastructure in this research.

Approaching energy infrastructures as socio-technical systems implies perceiving them as complexes of technical and institutional or social elements are heavily interwoven. Central to this view of infrastructures is that "socio-technical systems are erected and structured around a certain technical core of physical artifacts [and their connections and that they are] embedded in, sustained by, and interact with comprehensive socio-historical contexts" (Ewertsson and Ingelstam 2004, 293; see also Hughes 1983, 465).[19]" In other words, not only are the material technical components and installations taken into account (e.g. wires, switches, and transformers), but also the individuals and organizations that develop, operate, use, and govern the system, as well as the institutional framework (ownership, organizational structure, and regulatory framework) under which they carry out their activities and which embodies the existing cultural values and specialized professional know-how (Kaijser 2005, 12-13; Ewertsson and Ingelstam 2004, 293). The obvious strength of this perspective is that it does not treat infrastructures solely as technical systems exclusively following a common technical topology (like Barabasi 2003, Newman 2003, Sahal 1993) but broadens this perspective to include social and organizational elements that are considered crucial and integral parts of systems and their performance (Kroes et al. 2006 and Jonker 2010, 17-18). The key consequence of perceiving infrastructures as socio-technical systems is that infrastructure behaviour cannot be understood by "merely looking at the structure and dynamic behaviour of either the physical or the social network" (Weijnen and Bouwmans 2006, 124), since both are interconnected. The reliability of infrastructures, therefore, is "determined by the performance of the integrated system, i.e. the integrated physical and social network" (Weijnen and Bouwmans 2006, 124).[20] Let us hence discuss the technical

[19] "This technical core may consist of many technical subsystems and components and is often functionally dependent upon other [large technical systems]. The technical devices in a large socio-technical system are not self-supporting or self-adjusting" (Hughes 1983, 465).

[20] Rinaldi et al. (2001, 13), writing on infrastructures as complex adaptive systems (CAS), note in this regard that when "large sets of components are brought together and interact with one another [in an orderly fashion], synergies emerge" that a mere aggregate of components working together in an ad hoc fashion would not deliver. The assets of the electricity system for example are placed in a well thought-through manner.

and social dimension in detail (and in light of reliability) before elaborating their interrelationship and its effect on infrastructure performance and reliability.

2.2.1 The Technical Dimension of Energy Infrastructures

Technologies can be fairly straightforwardly defined as the technical assets or artifacts involved in the operation of an energy infrastructure. They are such tangible objects such as pipelines, wires, pressure stations, generation plants, control systems, etc.[21] However, "[t]he point of departure for studies on 'technology-as-systems' is that many technologies cannot be studied merely as isolated physical artifacts. Instead – like anything properly called 'a system' – they are part of complex larger wholes of interacting, inter-connected components which support and sustain them" (Ewertsson and Ingelstam 2004, 305). When discussing the technical dimension of infrastructures, it is therefore helpful to look at the literature on large technical systems (LTS). Joerges (1988, 24) defines LTS as "those complex and heterogeneous systems of physical structures and complex machineries which (1) are materially integrated, or "coupled" over large spans of space and time, quite irrespective of their particular cultural, political, economic and corporate make-up, and (2) support or sustain the functioning of very large number of other technical systems, whose organizations they thereby link."

Where energy infrastructures distinguish themselves from other LTS is in the network features they harbour. First, infrastructures consist of various nodes and links, i.e. are made up of different technical components. Whereas the nodes consist of geographically fixed, tangible assets that produce, store, refine or sell a product, the links make up the long-distance or local network that distributes the product between the nodes. "This means that network effects are present, such as complementarities, compatibility, standards and network externalities" (CPB 2004, 17). The physical network is the key feature of infrastructures vis-à-vis other technical systems because it is unlike the transport of a product between companies (which merely breaks an assembly line in parts). It also separates energy infrastructures from, for example, financial markets. Second, energy infrastructures are "characterized by the presence of a piece of the network infrastructure which is essential for the system to function and by the strong interdependency of the users' actions" (CPB 2004, 18). As such, failures in one part of the infrastructure may affect or cascade to another part, making reliability a system-wide property. Finally, energy infrastructures are "often characterised by large lumpy and/or sunk investments, and large economies of scale and/or scope" (CPB 2004, 18). Because of these technical characteristics, network industries are often characterized as natural monopolies.

[21] Although technologies are often intended as tangible artifacts, they sometimes also include ideas. To avoid such a difficult distinction, Saviotti (2005, 12) defines technology as "the set of activities by means of which human beings modify their external environment." In practice however, these 'activities' mostly come down to technical artifacts. A very basic example would be a pipeline. In this regard, a pipeline allows us to engineer the physical environment by recreating our understanding of geographic location and distance through transportation. Hence we take technologies to be artifacts.

Energy infrastructures are often separated into different segments such as upstream and downstream, generation and network, production and distribution, etc. Let us clearly outline what we understand to be energy infrastructures and their various components by discussing the supply chain. See also Figure 2.1 below. Generally, three main parts of an infrastructure are distinguished: generation of the energy source or carrier, the network that transports the energy source or carrier, and the application that utilizes the energy source or carrier. These three parts are subdivided into several components that represent smaller, technically distinguishable entities.[22]

Generation consists of "the energy sources and their exploration, the production, conversion and refinement of the raw material, and the wholesale trade on the related energy market" (UCP 2010, 20). For instance, electricity is generated in power plants from fossil fuels, renewables, or in nuclear reactors (entities sources and production). The entity production is also responsible for the refinement or conversion of the energy source. Afterwards, the produced energy source or carrier is traded on the wholesale market by energy companies. The entities trade and production may be heavily interwoven. For example, the entity trade orders production assets based on their capacity and price. The combination of this ordering, energy market prices, and the "operational boundary conditions" (UCP 2010, 20) of production facilities then determines the fuel mix and which facilities should generate it. So the entity trade is in essence involved in fuel procurement.

The network is the core feature of energy infrastructures and entails the transmission and distribution networks, the storage facilities, and the metering of energy delivered. The transport of energy (electricity, natural gas, or oil) from production sites to end users is handled by network companies; the Transmission System Operators (TSO) for the long-distance (national and international) and large-quantity transmission networks (high-voltage grids or high-pressure pipelines) and the Distribution System Operator (DSO) for the short-distance (local and regional) and low-quantity distribution networks (low-voltage grids and low-pressure pipelines). This involves balancing the load in real time, scheduling power flows over the grid, dispatching energy as ordered, managing congestion, setting up emergency procedures and support services, managing information flows, and handling financial settlements (Amin 2000; Schulman et al. 2004). Additionally, TSOs and DSOs also watch over power and gas quality, "e.g. the load balancing electricity and gas quality processes, usually under a regulated regime" (UCP 2010, 20). TSOs generally have a more

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[22] We prefer to use the term 'entities' over 'actors' or 'organizations' because we are dealing with them as nodes and links in a technical system, each of which has to perform their task for the overall system to function. We do not see them as actors with their own interests, i.e. or having economic preferences that may be contrary to reliability considerations. Such considerations should not be part of an exercise to find the organizational requirements of the technical functioning of renewable energy systems.

In addition, the term entity is chosen because it refers to more than just a technical asset; it is a collection of functionally related assets that has a distinct role in the operation of an infrastructure. Examples are the transmission grid, a power plant, a storage depot, or a retail outlet. Please see Rinaldi et al. (2001, 21) for an alternative classification of infrastructures and their technical scales.

prominent role than DSOs in managing network operations; they have more data acquisition, analyses, and control abilities in order to dynamically reroute energy flows and prevent failures (UCP 2010, 117). In contrast, DSOs tend to merely signal and fix what has been broken. This difference is mostly due to an energy market where large-scale energy producers feed-in their energy at the transmission level; hence balancing takes place there immediately. The storage of energy is often taken care of by network companies and traders. Storage may not always be a possibility. Electricity, for example, may lack the storage facilities or depots of natural gas and oil networks. The next entity in the energy chain is metering which "provides all services associated with the metering process" and is therefore of great importance for the "adequate functioning of the energy market [because] all other entities in the value chain make use of meter data in some aggregated form or another" (UCP 2010, 20).

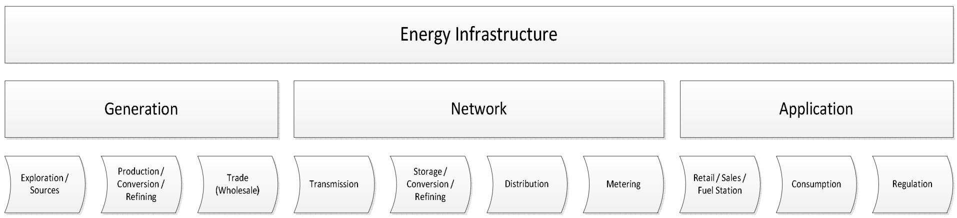
Finally, the application part encompasses the components or entities that sell energy, such as sales companies and fuel stations (often named retailers or suppliers), and the final consumer that utilizes the energy for all kinds of motive and stationary (household or industrial) applications. Retailers interact with clients, communicating directly to the consumer or end-user (both business and households). The consumer "in the end pays for the entire energy value chain, including the transaction costs [and governance regulation] that are required for proper functioning of the energy market" (UCP 2010, 20-21). One might also consider regulators as another entity active in this part of an infrastructure. While regulators are not involved in the daily operation of energy infrastructures as such, and are usually not considered part of the supply chain of infrastructures, the impact of their regulations on daily operations does urge for their incorporation (Gómez-Ibáñez 2003). If so, it seems best to position them after the consumers for it is them that they seek to serve and protect.

Though there is considerable diversity possible among energy chains, with different infrastructures being composed of different components, there are nevertheless some distinguishable ideal-types. A common distinction in this respect is between centralized and decentralized generation possibilities and transport networks. Centralized systems refer to those infrastructures with a high complementarity between components, i.e. when the operation of the nodes and links involves constant readjustments between components. Decentralized systems in turn entail low levels of complementarity, i.e. when the various components can operate autonomously and the overall system functions none the worse because of it. In general, centralized infrastructures are characterized by a few central large-scale production facilities and a national interconnected network, while decentral systems refer to the presence of many local smaller-scale production sites and several independent local networks. Based on these central or decentral production and network choices, four general ideal types can be imagined.[23] First, there is the traditional tree type structure, in which

[23] In a similar fashion, Egyedi et al. (2009, 1, 3-4) distinguish between the Hughesian large-scale technical systems (LTS) as the current dominant paradigm of infrastructure design and inverse infrastructures, which seem to follow a different mode of technical operation and path of development. Whereas the LTSs can be characterized as provider-driven, government-driven, top-down, centralized, large-scale, predictable development outcome, initiated by providers / large companies / government, the inverse infrastructures, can be described as

a few central production facilities generate the energy that is then gathered and transported through a national transmission network that branches out into several distribution networks. Second, there is the opposite structure, in which energy is generated locally by small-scale or onsite production facilities and which require only local distribution to get to customers. This would resemble energy systems as islands in terms of operation, but islands that nevertheless together provide nationwide service. Third is a round-a-bout type of system in which production is decentralized, but the energy is still distributed in an interconnected or centralized fashion. Production facilities just feed their energy in at different points in the national network, which itself need not be restricted to energy flowing in one direction only. Finally, there exists the possibility of having a few separated networks supply customers with energy from a few central production facilities. This would be the case if each central facility supplies its (specific) energy source or carrier to a network that serves only it.[24]

Figure 2.1 Energy infrastructures supply chains



Looking at the supply chain, we may distinguish two aspects of ensuring reliability from a technical perspective. First is the actual functioning of the assets involved, e.g. the pipelines, wires, pressure stations, production machinery, etc. Second is the operation of the system as a whole, i.e. how the complementarity between the assets of the various supply chain entities is maintained. This research focuses exclusively on the latter, assuming the technical soundness of infrastructure assets as such. The reason is that we are interested in those aspects of reliability that are related to organization. While the malfunctioning of technical assets may cause severe inconveniences to the reliable delivery of energy, the repair of such assets would

user-driven, self-organized, bottom-up developed, decentralized control / operation, bottom-up investments by many, small-scale / local, unpredictable outcome of development, initiated by users / companies. However, in their definition, it seems that many traditional infrastructures have a more clearly identifiable physical network than inverse infrastructures. Though this could be seen as making the distinction irrelevant for energy infrastructures, the fact is that developments in ICT provide the energy transition with numerous options for more decentralized or distributed forms of generation.

[24] A final note on this matter must be made, however. The distinction between central and decentral is often dependent on the geographic scale one looks at. "A centralized institution in one context or country may be a local or regional institution in different circumstances or in a different place" (Lucas 1985, 284).

reestablish normal operations. One may, for example, replace a broken electricity wire. Problems with the complementary operation of assets of different entities (that are all functioning well from a technical perspective), in contrast, constitute more than a 'mere' technical issue. Entities need to coordinate operations and take care of their specific tasks while keeping an eye on other entities' tasks to ensure that energy flows reliably from producers to the consumers. Hence, system operations may be distinguished from asset management in this regard. Let us therefore elaborate upon these concepts of operation and complementarity.

To ensure the reliable operation of energy infrastructures, the various nodes and links that comprise them, i.e. the industries and networks, need to work together in a complementary fashion and in a certain order to produce the desired end-product. "Typically, nodes and links cannot be used at random, but need to be approached in a coordinated way in order to produce a specific service" (Finger et al. 2006, 4). From a technical perspective, "this coordination is very elementary to safeguarding the functioning of the system" (Finger et al. 2006, 4). This is not so easy to achieve; the more nodes, the more complex the system. In addition, these nodes are not passive. They "interact with and adapt themselves to their surroundings. Their reaction to external changes is often non-linear, which can result in unpredictable behavior of the system as a whole" (Weijnen and Bouwmans 2006, 125). In such a setting, safeguarding system integrity is an important priority for ensuring the technical functioning of energy infrastructures. Technical integrity "implies a need for the capacity of the overall system to correct errors or unexpected outages of network elements in a way that operations can be maintained, at least in parts of the infrastructure" (Finger et al. 2006, 4). Without network integrity the production and allocation of a product or service simply cannot take place.[25]

Two categories of disruptive events are commonly distinguished that affect technical integrity in infrastructures in general.[26] "First, there are the routine events that, although disruptive, are largely taken for granted by society" (De Bruijne 2006, 8). These include traffic jams, flight delays, temporarily changed railway schedules, slow internet connections, or occasional empty fuel stations. "Second are interruptions of services due to small-scale failures in critical infrastructures" (De Bruijne 2006, 8). These may be electricity blackouts or flight and train cancellations. Though less frequent than the routine failures addressed above, their effects may be more harmful. Focusing on the latter category, many causes for malfunctioning, service interruption or quality loss can be distinguished. There are natural disasters

[25] This focuses a discussion of infrastructure reliability on the network. That is not to say that generation and application are not relevant, but it is to say that it is helpful for a discussion on reliable technical functioning to focus on the network discussing generation and application in relation to the network. As such, production sites and consumers are treated as network entry and exit points respectively. Referring to 'infrastructure technologies', then, still includes all technical artefacts involved in the various infrastructure components that are required to operate an infrastructure.

[26] According to De Bruijne (2006, 55) in "large-scale, complex systems, 'incidents' such as equipment malfunctions or small failures occur almost continuously. Accidents that damage or threaten to do damage happen daily or weekly. 'Serious accidents', which halt the process of the system or a major subsystem, occur perhaps once every two to three months."

(storms, earthquakes, flooding), human errors (ignoring signals, lack of attention, overlooking or disregarding instructions), maintenance work (accidents during repair or excavation works, starting-up and shutting-down is not business as usual), sabotage (of power plants, transmission wires or pipelines or trucks, terrorism), the wear and tear of specific components (lack of maintenance), and capacity overload (handling peak demand, blackouts) (Weijnen and Bouwmans 2006, 122-123).

Fortunately, failures in one part of an infrastructure or complex system often remain contained because system designers are aware of such eventualities and plan for them through redundancies, back-ups, emergency procedures, and control mechanisms. Control mechanisms or control systems are "used to coordinate the flow of goods, traffic, materials, funds, services or information through complex supply, production or distribution systems" (Nightingale et al. 2003, 477-478).[27] These may include computerized monitoring systems, routines and emergency procedures, preventive maintenance, switching stations, etc. Well-known examples are the supervisory control and data acquisition systems (SCADA) and energy management systems (EMS) (Rinaldi et al. 2001, 14). Control mechanisms can help reroute energy flows on short notice but also "significantly improve the allocation of system traffic" on the longer term.[28] System modernization efforts often involve the development of better control technologies, with the role of ICT as an important enabler or source of innovation and economies of systems (Nightingale et al. 2003, 479).[29] In addition, redundant nodes and links also help to circumvent failures while infrastructure design may take important technical reliability principles into account, like the N-1 design principle wherein a system of N components should be able to continue operations if a single component would randomly fail (Barabasi 2003). We may make a distinction between more centralized control and more distributed control. "In centralized

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[27] According to Nightingale et al. (2003, 484), "control is required when a match between actual and intended performance cannot be reliably maintained, typically because requirements change or cannot be designed-in. In these instances control systems monitor, compare and modify the inputs and parameters of various subcomponents in a co-ordinated way to ensure that the overall system behaves as intended."

[28] Nightingale et al. (2003, 489-490) point out in this regard that "[c]ontrol innovations can increase capacity utilization if they optimize performance over a larger number of interdependent components [and] increase the accuracy of control, its speed or reliability. [Moreover, as] performance becomes more dependent on control, control systems can be bundled-in, creating an increased emphasis on systems' reliability and potentially changing the social distribution of risk" among the firms involved in coordination. Finger et al. (2006, 4) also note that coordination or control mechanisms could optimize economic efficiency. High degrees of complementarity might lead the improvement of "the utilization of the installed capacity, creating economies of system that are distinct from the traditional economies of scale, speed and scope."

[29] Nightingale et al. (2003, 488) note in this regard that the "relationship between the control architecture and the system's performance creates an important distinction between systems carrying physical and informational traffic. […] In systems where the traffic is physical, such as trains on a network, or chemicals through a processing plant, an additional information gathering systems must be placed on top to monitor and control the physical process. The two systems architectures must be optimized together."

control architectures, system performance is monitored and controlled through a few high-capacity control centers that direct changes to and from the center. In distributed architectures, greater control is exercised at the periphery, typically by human operators" (Nightingale et al. 2003, 488). As a consequence, changes in control can have "important implications for a system's architecture and performance" (Nightingale et al. 2003, 488). As such, control mechanisms or control systems pose certain requirements on the tasks of entities and their interaction (or entities' responsibilities and coordination requirements as we will see in the next section). This brings us back to the organizational requirements of reliability.

Because of these control mechanisms and redundant assets most failures are dealt with in time, i.e. before they escalate. Massive failures only tend to occur when a system experiences multiple failures in design, equipment, operators, procedures, or environment at the same time (Perrow 1999a, 1999b). However, when multiple failures occur, they "have the potential to spread and cascade when they interact in a way that was not anticipated by either system designers or those operating large-scale complex systems" (De Bruijne 2006, 53). Such a cascade effect[30] is extremely difficult to stop once started and often results in system-wide failure. A number of factors contribute to the likelihood of a control failure / the occurrence of a cascading event and influence the reliability of a technical system[31]: the size, scope and (interactive) complexity of the system (Amin 2000), the degree of interdependence of the components of the system and of the system with other systems with regard to energy traffic (i.e. the level of coupledness), the diversity of functions networks serve, "the relative speed of traffic flow compared with the speed of control" (Nightingale et al. 2003, 490-491), and the trade-off between the pursued productivity and reliability. Basically, "[t]he bigger and more complex the physical system employed and the bigger and more complex the organizations that run them, the greater the chance that failures will occur simultaneously and result in disaster (Rochlin, 1989:171; Sagan, 1993:3; CAIB, 2003:97)" (De Bruijne 2006, 55). Hence some urge to limit the complexity of interaction and strong interdependencies between components when designing energy infrastructures (Perrow 1994a, 1994b).

2.2.2 The Social Dimension of Energy Infrastructures

The social dimension of energy infrastructures consist of two core aspects: actors and their interaction plus the formal and informal institutions involved. Both are intimately related. The result is that the social dimension represents an extremely complex interplay of actors and factors whose diversity in outcomes and appearances can hardly be overstated or overlooked. Organization is a specific aspect of this social dimension and is a manifestation of actors' interests and the broader institutional

[30] "A chain of events that creates failures which increase in scale and quickly ripple through the large-scale complex system until so many sub-systems are affected that – in the end – the entire system fails" (De Bruijne 2006, 54).

[31] Perrow calls these 'error-inducing characteristics' that "influence the frequency, spread and management of failures and the tightness of coupling among risky systems" (De Bruijne 2006, 58).

environment that enables and constraints possibilities for actor behavior and interaction. On the one hand it are the interests of actors and the existing rules and regulations that determine the way things are and may be organized; on the other hand, once in place, organizational structures determine the possibilities for actors to interact to achieve a certain goal, such as reliability. Let us elaborate.

The actors of energy infrastructures are basically the private and public entities that represent the various technologically separable components of the supply chain: source delivery companies, energy producers and suppliers, transmission operators and distribution companies, storage facilitators, metering and service providers, consumers, regulating institutions, and government policy makers. However, one should also keep complementary industries or interrelated infrastructures in mind. Each actor is "an agent who acts according to a set of rules determined by legislation and regulation, moral and cultural codes, etc. [and] its own strategy" (Weijnen and Bouwmans 2006, 127).[32] On the one hand, because actors compete in infrastructure-related markets, "business economics and strategy will influence the actor's behaviour"[33] (Weijnen and Bouwmans 2006, 127). Depending on the interests sought, entities may either cooperate to achieve a common goal or else try to achieve a goal autonomously. On the other hand, policy makers and regulators set boundary conditions to their behavior in the form of rules and restrictions and incentivize them through public service obligations and reliability performance targets. Hence, actor behavior is a mix between structure and agency, i.e. between the institutions that enable and constrain them, their own interpretation of this environment (mental maps), and the pursuit of their particular interests. Actor interaction can take on a variety of forms, but generally interaction is either more collaborative or competitive, more interdependent or autonomous, and more hierarchical or horizontal in nature. Interaction also depends on the amount of actors involved in a sector or infrastructure, their roles and responsibilities, their relative power position, and the nature of the actors (public or private).

The other aspect, institutions, represents the environment in which the actors operate and by which they are influenced. Institutions are "usually credited with establishing patterns of human interaction, by excluding some types of behaviour and encouraging others" (Saviotti 2005, 12-13), or as "the rules of the game" (North 1990). More attuned to technical systems, "[i]nstitutions or institutional arrangements are […] a set of rules that regulate the interaction between parties involved in the functioning of a (technological) system" (Koppenjan and Groenewegen 2005, 244).

[32] Lucas (1985, 263) writes in this respect that the actors "which control the supply and use of energy have a variety of corporate objectives; their operations are subject to a varying extent to the sanction of the market and the law. Public and private companies will plan in part according to objectives set by regulation of statute or formulated internally to anticipate the expectations of shareholders. But there is more than this to the motivation of companies; it is well-known that organizations develop a concern for their own security, future well-being, and growth which is almost organic."

[33] For example, an "incumbent actor may drop prices in order to try to keep new entrants from the market, whereas a new entrant may lobby for tighter restrictions on the incumbents' strategic behaviour" (Weijnen and Bouwmans 2006, 127).

Many aspects of institutions can be distinguished. Williamson (2000, 597), for example, distinguishes between four layers that each deal with a different aspect. The first deals with the informal institutions of traditions, customs, values and norms; the second with the formal state institutions, ownership matters, and regulatory issues (that set the rules of the game); the third with governance arrangements (transactions or play of the game); and the fourth with resource allocation and employment. The origin and nature of institutions can be found in underlying economic, political, socio-cultural, environmental, and technical trends and developments. They shape the situation to which institutions respond. Despite the immense institutional diversity that exists across various countries, there are nevertheless a few ideal-types that can be distinguished. Commonly, institutional settings are differentiated on a public-private scale: between top-down and bottom-up direction of initiative and governance, between more or less government intervention in the market, and between public and private types of actors. Political economists distinguish for example between the Anglo-Saxon, Rhineland, and Asian Corporatist model. More attuned to energy policy, Lucas (1985, 265-268) distinguishes between state led and market approaches, separating the former into a regulatory and control variant. Though more focused on governance rather than institutions as such, they nevertheless cluster key institutional differences along similar public-private lines.

The notion of organization, on which this research focuses with regard to reliability, represents a specific aspect of the social dimension of socio-technical systems. While a common term in both the New Institutional Economics field and literature on accidents in large-technical systems, a proper definition of the term itself is often lacking at the costs of defining organizations as firms etc. or a focus on the various types of organizations or organizational structures. Let us therefore start by elaborating what we understand by organization and organizational structures. Organization is defined by the Oxford dictionary as "the way in which the elements of a whole are arranged" (Oxford dictionary, 31-07-2011.[34] As such, an organizational or management structure[35] determines the "relationships between functions and positions, and subdivides and delegates roles, responsibilities, and authority to carry out defined tasks" (Business dictionary, 31-07-2011). However, organization may also be defined as the "context and forms of coordinative structures" among entities (De

[34] This definition of organization should not be confused with that of organization as "an organized group of people with a particular purpose" (see http://oxforddictionaries.com /definition/organization for the full definition) or a "social unit of people, systematically structured and managed to meet a need or to pursue collective goals on a continuing basis" (http://www.businessdictionary.com/definition/organization.html). This refers to firms or other business units.

[35] Grabowski and Roberts (1996, 7) state in this regard that in "organizational literature, the concept of structure is usually understood to mean the configuration of activities in an organization that is enduring and persistent, and provides the organization's patterned regularity, or the anatomy of the organization, providing a foundation within which the organization functions. This view is sometimes called the positional view of structure. Alternative to the positional view are relational and cultural views of structure, which view networks of systems, people, and groups."

Bruijne 2006, 74). In this definition organization is closely related to the concept of coordination, i.e. "the synchronization and integration of activities, responsibilities, and command and control structures to ensure that the resources of an organization are used most efficiently in pursuit of the specified objectives" (Business dictionary, 31-07-2011) or "the organization of the different elements of a complex body or activity so as to enable them to work together effectively [and/or a] cooperative effort resulting in an effective relationship" (Oxford dictionary, 31-07-2011). Combined, these definitions identify two core aspects of organization and organizational structures. Whereas the former definitions seem to be more related to the 'who does what, when, and how' whilst organizing an activity (relating to the entities[36] involved in organization), the latter definitions emphasize the nature of entity interaction in terms of being either hierarchical / top-down, horizontal / bottom-up, or something in between.[37] Consequently, different organizational structures may embody different responsibilities for the entities involved in an activity and a different nature of their interaction.

The fact that organizational structures embody the division of responsibilities among entities and shape how they may coordinate their actions makes them important for the reliable operation of infrastructures (Bourrier 2005, 102). First, we already saw earlier that technical operations, i.e. the functioning of assets and control mechanisms, imply specific responsibilities for entities and may pose more or less stringent coordination requirements among them.[38] This links organizational structures directly to technical operations. Second, because organizational structures embody entities' responsibilities and interaction possibilities, they set the boundary conditions for entities to coordinate for operational control, i.e. define entities' daily tasks and enable and constrain certain forms of interaction. Grabowski and Roberts (1996, 2), for example, write in this regard that human error is often "embedded in organizational and societal processes that ultimately result in the error." In this sense, it is believed that centralized and hierarchical organizational structures are suited to facilitating frequent communications and complex interactions among supply chain entities in highly interdependent systems[39] because they minimizes conflicting interests

[36] We continue at this point to discuss actors as entities with a specific role in the functioning of the overall infrastructure system, rather than the economist's actor with its associated interests and initiatives.

[37] According to Pugh et al. (1968, 72-79) centralization has to do with "the locus of authority to make decisions affecting the organization. This identified the level in the hierarchy where executive action could be authorized, even if this remained subject to a routine confirmation later, for example by a chairman or a committee."

[38] Now that we have defined two aspects of organization, we may rewrite the organizational requirements of technical operation more accurately by zooming in on the particular operational responsibilities of entities regarding the functioning of technical assets and control mechanisms and the coordination requirements among entities that complementarity may bring with it.

[39] To illustrate, transmission and distribution network operators need to continuously coordinate their efforts to ensure energy flows from A to B, i.e. need to know how much goes in and out of a network and need to coordinate this with energy production facilities. Poor

among entities, put entities in close proximity, create a shared business culture, and allow for top-level, central control and decision making that has the overview to manage cascading events (Grabowski and Roberts 1996, 3). On the downside, hierarchical structures might be less flexible due to established routines, procedures, and operational practices that may hinder the formation of new coordination relationships and quick adaptation to new emerging situations (Shrivastava 2009, 1365). In short, they are slow and rigid. Decentralized and horizontal organizational structures, in contrast, allow supply chain entities to autonomously operate their part of the infrastructure and communicate and coordinate with each other on an exception basis without a detrimental effect on overall system reliability (Grabowski and Roberts 1996, 3). The flexibility that such a structure presents to entities allows them to address accidents immediately at the root of the problem (before they cascade) and without the need to wait for higher-level approval. On the negative side, decentral structures risk miscommunication, diverging operational priorities and cultures, overlapping responsibilities, and general confusion or ambiguity (Shrivastava 2009, 1365). Moreover, decentral systems will need to maintain buffers or 'decoupling mechanisms' (i.e. inventories, excess capacity, waiting lines) and will need to ensure that each entity behaves in a manner that is beneficial for the system as a whole (Grabowski and Roberts 1996, 3). Hence, from an organizational perspective, maintaining reliability is all about how organizational structures define the responsibilities of the entities involved and shape the possibilities for them to interact in order to coordinate for control.[40] In this light, it is interesting to look at how liberalization and unbundling has affected the amount of entities, their public and private nature, their responsibilities in the operation of infrastructures and the nature of their relations, such as in the California electricity crisis for example (Joskow 2001; Hughes 2000); and how this switch from a single integrated entity to many autonomous entities in turn created challenges for system operations.

Variations in organizational structure have been traditionally based upon differences in "the number of organizational units required for decision-making […] and the interdependence of those units" (Grabowski and Roberts 1996, 8), usually ranging from centralized forms of management to autonomously operating units (Adler and Shenhar 1990, 30). When it comes to distinguishing between different organizational structures, the concept of vertical integration of firms (Williamson 1979; Harrigan 1984, 1985; Perry 1989) and networks of actors (Provan and Kenis 2007) prove particularly useful because they conveniently capture both aspects of organization identified above. Vertical integration is generally described as the degree to which a firm owns its input suppliers and its output buyers or "the process in which several steps in the production and/or distribution of a product or service are controlled by a single company or entity, in order to increase that company's or

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communication and ambiguities among the control centers of different entities as a consequence of organizational structure needs to be prevented.

[40] Entities need the means to coordinate as they should in order to ensure reliability. Whether they make use of the possibilities is another question entirely. Human error will always remain an uncertain factor.

entity's power in the marketplace" (investorwords dictionary, 31-07-2011).[41] There are many reasons for a firm to vertically integrate with another (Joskow 2005; Ménard and Shirley 2005; Mulder et al. 2005; Mulder and Shestalova 2006). Most of them are economic in nature, i.e. to capture profit margins, reduce costs by producing products internally, input security, opportunity to differentiate, less information imperfections, increase barriers to entry for competitors, etc. Of course, vertical separation may provide the opposite: decrease bureaucratic / overhead costs, create competition among suppliers and buyers to lower prices, increase product variety, etc. There are however also more operational reasons for vertical integration: improving supply chain coordination, facilitating investment in highly specialized assets, and avoiding capacity-demand-supply balancing issues. Drawbacks to vertical integration in an operational sense usually include the loss of flexibility to respond to market developments and the responsibility to ensure capacity-demand-supply balance. Moreover, in "the absence of alternative input sources, the integrated firm may be compelled to build excess upstream capacity to meet the downstream demand in all conditions" (Garcia et al. 2007, 793-794).

The existing literature identifies various degrees of vertical integration. Williamson (1979), differentiates between four types of governance structures that coordinate transactions (based on the asset specificity, uncertainty, and frequency of the transaction in need to be governed)[42]: classical contracts (in which rights and obligations are clearly specified), an unified governance structure where coordination resides in one decision making center (representing a vertically integrated hierarchy), a bi-lateral governance structure wherein two parties "have created a specific joint organisation, which coordinates the transaction", and a tri-lateral structure that may occasionally be required to govern transactions between multiple actors (suppliers and buyers) (Groenewegen 2008, 10). Similarly, yet not identically, Harrigan (1984, 642-644) distinguishes four alternatives when it comes to vertical integration strategies that firms can follow. These are non-integration, quasi-integration, taper integration and full integration. While the extremes reflect the polarized private contracting and centralized hierarchy ideal-types, the two intermediate represent either cooperative ventures as a form of non-contractual ownership (quasi-integration[43]) and a situation in which firms partly integrate and partly buy their upstream or downstream activities

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[41] Put differently, "inherent in the notion of vertical integration is the elimination of contractual or market exchanges, and the substitution of internal exchanges within the boundaries of the firm" (Perry 1989, 185).

[42] Ghoshal, S. and P. Moran (1996) however doubt whether these transactional factors alone are able to capture the essence of why vertical integration into firms or organizations takes place.

[43] This type of quasi-integration should not be confused with a situation in which two firms have separate ownership but where one firm may determine the actions of the other. Rather, it merely implies that firms "need not own 100 percent of the adjacent business units in the vertical chain to enjoy the benefits of bonding their interests to other firms' interests" (Harrigan 1984, 642-643). Examples of quasi-integration would for example be cooperative ventures, minority equity agreements, or loans or loan guarantees.

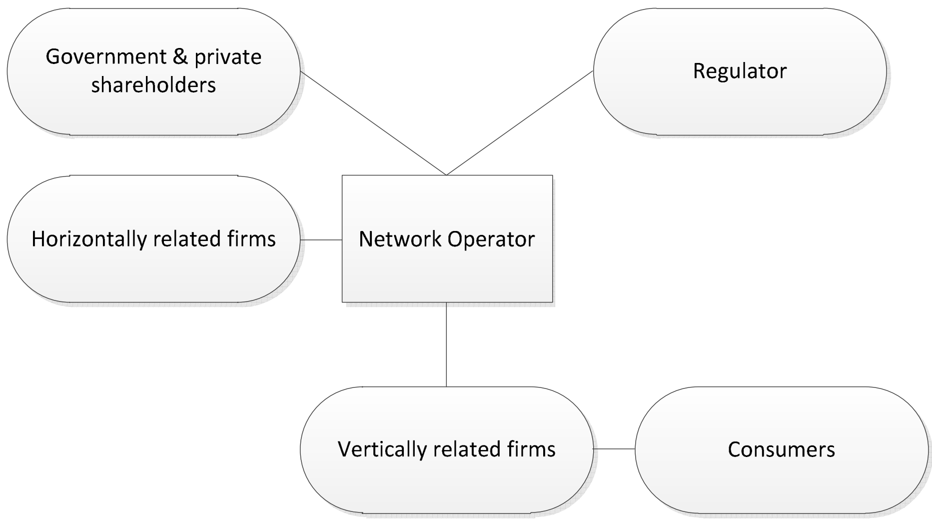
(taper integration).[44] Finally, in the literature on actor networks, degrees of vertical integration or separation are commonly based on the amount of actors involved, their role or relative position in the operation, and the nature of the actors (public or private). Provan and Kenis (2007), for example, differentiate between four vertical integration strategies to ensure best coordination and cooperation. First is a form based on private contracting between the members of a network of organizations / actors in a decentralized way. Here, "every organization [i.e. actor] would interact with every other organization to govern the network" (Provan and Kenis 2007, 233-234). The network is hence completely governed by the organizations that comprise it. Second is a hierarchically, or brokered, form in which a single network member or lead organization would be responsible for network governance and performance. In that case there are only "few direct organization-to-organization interactions, except regarding operational issues such as the transfer of business, clients, information on services, and the like" (Provan and Kenis 2007, 234). Third and fourth, Provan and Kenis also hint at two possible semi-brokered forms, where one organization might take some key governance activities leaving others to network members or forms where (various) groups of network members take shared responsibility for certain governance tasks and no single member has any significant leadership role. In addition, organizational theory in turn identifies three (inter)organizational coordination structures that "dominate current thinking on networks of organizations [i.e. entities]: markets, hierarchies and networks" (De Bruijne 2006, 72).

At this point, we propose to differentiate four general organizational structure ideal-types particularly attuned to technical operations to have as a reference point in our further discussion. They are very similar to the four strategies of Provan and Kenis though also contain elements of Williamson's four types of governance structures. First is 'vertical integration'. Here, infrastructures are organized by a single entity that coordinates all upstream and downstream technical operations from production to transmission, distribution, and retail in a top-down fashion from a central control center. Second is 'lead entity' in which several entities have formal responsibility for their part of technical operations but where a single entity (frequently the transmission system operator) acts as a lead organization for key coordination activities. Third is 'common operation'. This more decentral structure of organization represents the situation in which each entity is essentially autonomous in executing their technical responsibilities, but in which groups of entities may share the responsibility / have to coordinate for certain control mechanisms while none of the entities has central authority. Fourth is 'incidental coordination', a strongly decentral organizational structure in which entities coordinate only when occasionally required and in such a way that bilateral interaction between the relevant entities is usually sufficient.

[44] Degrees of vertical integration can be differentiated by studying a) the breadth of integrated activities undertaken and the number of tasks that firms perform in-house; b) the number of stages of integrated activities; c) the degree of internal transfers for each vertical linkage; and d) the form of ownership used to control the vertical relationship (Harrison 1984, 640-644).

Currently, the organizational structure of electricity and natural gas infrastructures is generally (and in our case, the Netherlands, as well) dominated by the central role of a transmission system operator (TSO). This network operator (defined as a network company and its management) is in charge of network planning, maintenance, investment, and market facilitation (CPB 2004, 23). It is responsible for real-time system operations and solving network congestions. The network operator commonly has relationships with four types of agents (see also Figure 2.2 below). First are the owners of the network operator, the government and/or private shareholders, "which *internally* control the network operator" (CPB 2004, 23). Second is the regulator who has "*external* control over the network operator" by controlling "the relationship between the network operator and outsiders such as customers (regulation of prices, monitoring reliability, etc.) and other firms (regulation of entry, access pricing, etc.)" (CPB 2004, 23). Third, the TSO is horizontally related to "competitors in the same region and also to its 'peers' in other regions" (CPB 2004, 23). Finally, and most importantly for this research, the network operator has "vertical relationships with production companies, maintenance firms, suppliers that use the network to transport their goods and services to customers, and so forth. In practice, the network operator may or may not be integrated with these firms" (CPB 2004, 23).[45]

Figure 2.2 Energy sector organization: the network operator as the central actor



Source: Adapted from CPB 2004, 24.

[45] The current transmission operator-focused approach to network operation resembles the lead organization type of interaction or coordination as depicted earlier.

2.2.3 'Coherence' - A Theory on Infrastructure Performance

Describing the two dimensions of socio-technical systems in order to understand them is one thing, having a theory to make statements on the effect of the relationship between technologies and organization on reliability is quite another. The same goes for having the ability to establish which organizational structures complement a particular technical system's operation and control mechanisms.

In a number of recent studies (2005-2010), Finger, Künneke and Groenewegen have developed the foundations for such an exercise. Having studied the relationship between technical and institutional dimensions of several infrastructures (electricity, gas, railways, post), they hypothesize that the economic, social, and technical performance of infrastructures is dependent on the 'degree of coherence' between the technical and institutional scope of control and coordination mechanisms (Finger et al. 2006, 13). By analyzing infrastructures before and after liberalization, they showed that due to privatization and deregulation performance[46] differed because institutional changes were not matched by technical ones. In a liberalized setting "the infrastructure business is decomposed into regulated and commercial components that are forced to operate independently from each other. Under these conditions, there is no economic or other incentive to optimize the system's complementarity" (Finger et al. 2006, 4). At the same time, the technical operation of the infrastructure still requires this complementarity to ensure the proper functioning of the whole, i.e. reliability. "This results in a very paradoxical situation" (Finger et al. 2006, 4); whereas the institutional coordination of networks has become decentralized, market-oriented and is guided by private-sector values, the technological coordination has remained to a large extent centralized, top-down organized and guided by public values. As such, non-matching organization of institutions and technologies adversely affected performance. Though the exact relationship between technical and institutional organization remained elusive in its specific effect on performance, the general notion that a certain degree of coherence between both dimensions is a necessity for ensuring basic infrastructure performance seemed established.

The authors are not alone in their argument. Joerges (1988, 27) and Kaijser (1994, 52) also differentiate between categories of tightly and loosely coupled systems to denote "the level of functional interdependence between various physical elements within separate systems, [which have] been conceived to correspond to the need of central and decentral interventions." Other examples of similar reasoning can be found in literature on the co-evolution of institutions and technologies (Abernathy and Utterback 1978, Saviotti 1986, 1996, 1998, 2005, Saviotti and Metcalfe 1991; Nelson 1994, Perez 2001, Dosi 1983; Murmann 2003; Unruh 2000; von Tunzelmann 2003; Von Tunzelmann et al. 2008), large technical systems (Hughes 1983, Ewertsson and Ingelstam 2004, Jackson et al. 2007, and Nightingale et al. 2003) and the socio-

[46] This performance is measured in terms of economic performance (static, dynamic and system efficiency and effectiveness), public values (affordability, availability, sustainability, quality) and technical system integrity (robustness, reliability and safety). The three performance criteria involve trade-offs among them.

technical transitions literature (Shackley and Green 2007, Geels 2002 and 2004). In the former, new technologies seem to require new institutions in order for them to develop, while existing institutions enable and constrain the technical choices open to pursue. On larger scales, technological product and process innovation and the development of industrial sectors seem to go hand in hand and industrial revolutions and shifts in the nature of corporate governance seem to develop in an interrelated fashion. In the latter two, infrastructure development seems full of examples wherein new technologies of network features pose new organizational (or control) and institutional requirements and wherein organizational constraints pose obstacles to the physical growth of infrastructures or the ability to control network operations (as we will see in the next chapter).[47] Yet the exact relationship between the technical and organizational dimension and its effect on performance (or reliability) also stayed unclear in these studies. Whereas cause and effect are observed, the mechanism through which they are related and transformed is far from being fully understood. In turn, these studies, as coherence, lack the ability to systematically move from energy systems' operational characteristics to their required organizational structures.

Perhaps the most concrete link between technologies and organization stems from the literature on technical economies of vertical integration. According to Garcia et al., technical economies of vertical integration may occur in energy infrastructures when physical interdependencies in the production process lead to economies of scope and coordination economies (Garcia et al. 2007, 793-794), i.e. when "there are significant technological complementarities across production stages or if using intermediate markets involves high transaction costs" (Garcia et al. 2007, 792). This is because a vertically integrated structure can "be a cost effective solution if there are substantial needs for coordination and adaptation across stages" (Garcia et al. 2007, 792). "Typically, in networks, joint optimization of production plant capacity and the size of the transmission system will lead to technological economies" (Garcia et al. 2007, 794). In their analysis of how to measure various sources of EVI[48] they

[47] Others also hint at this relationship. Williamson (1975) already hinted at the role of technologies in determining the level of vertical integration of firms. Though he focused clearly on economic determinants such as asset specificity, frequency and uncertainty, he also realized the potential effects of transactions across technologically separable barriers. Even further back, Hickson et al. (1969, 379) already asked the question in how far "technology determine[s] the form taken by the structure of an organization?" They remarked several studies in this regard. They found that "the type of technology available… sets limits on the types of structures appropriate for organizations" (Hickson et al. 1969, 379) and that increasing mechanization led to more formalized communication and changes in supervisory control and process support. What these cases showed was that "to operate a given technology, an organization must be of the requisite size" (Hickson et al. 1969, 395). Of course, this is related to firms, not the organization among firms as in energy infrastructures. Nevertheless, many of the findings are interesting and seem applicable.

[48] Garcia et al. (2007, 793) separate technical economies of vertical integration from transactional economies or economies due to inefficient input allocation as a result of upstream market imperfections. They follow in the footsteps of Perry (1989, 187-189) who also recognized that technological economies "may be an important determinant of vertical integration in some industries" next to transactional economies and market imperfections.

highlighted that "network industries (e.g. electricity, water, gas) [are] characterized by [such] strong technological interdependencies between production and distribution stages." For example, an electricity network may have a stronger need for centralized operation than does the distribution of oil. The need for coordination between electricity generation, and transportation, real-time management of power flows to guarantee the energy balance, and the fact that "electricity flows across the network in accordance with the laws of physics [and] cannot be controlled through a command and control system" calls for vertical integration and may "impose high externality costs in case of non-vertically integrated systems" (Garcia et al. 2007, 811). As such, strong technological interdependencies between production and distribution stages and strong coordination and adaptation requirements across the supply chain favor vertical integration. The truck distribution of petrol to fuel stations does not know these interdependencies and or coordination requirements. This is not to say that the oil sector is not vertically integrated, for it is. It is to say, however, that the oil sector is integrated for other reasons than technical. Oil companies "usually are involved along the whole value chain (exploration, production, transport and distribution), but their motivation seems to mitigate the impact of intermediate good price fluctuations / cycles and, hence to reduce profit volatility" (Garcia et al. 2007, 811).

It is tempting at this point to relate the four levels of centralization of infrastructure operation with the four levels of vertical integration of infrastructure organization. In this fashion, centralized technical systems would require the specific roles and responsibilities of entities and the nature of their interaction as present under the organizational structure of vertical integration or lead entity while more decentralized energy systems would require the structure of common operation or incidental coordination. Vice versa, different organizational structures would imply a preference for different technical systems. Although this would enhance the picture started by the coherence literature, it also lacks a sound scientific explanation why such a matching exercise would be valid. Thus while the concept of coherence provides a valuable hypothesis to start from, a framework to systematically establish the organizational requirements of specific energy technologies and their infrastructure networks remains elusive at this point. Nevertheless, if there is one lesson to learn from the perspective on energy infrastructures as socio-technical systems, it would be that maintaining reliability is all about ensuring the coherence between the operational tasks and coordination requirements of entities (in terms of degrees of centralization) and the organizational structures' division of responsibilities and coordination possibilities among entities (in terms of degrees of vertical integration).

The concept of coherence (backed by works on the co-evolution of institutions and technologies and insights on the technical economies of vertical integration) provides a useful starting point for thinking about a) reliability in socio-technical systems, b) relating the technical and organizational dimension to each other, and c) finding the organizational requirements of technical characteristics of energy infrastructures. This is an achievement that is often absent in more historical works on infrastructures that only manage to describe cause and effect, but fail to isolate the transmission mechanisms through which they are connected. Nevertheless, there are some important shortcomings that we need to note at this point.

First, the performance criteria include more than technical reliability, the focus of this research; economic criteria (static, dynamic and system efficiency and effectiveness) and public values (affordability, availability, sustainability, quality, safety) are also included. While this need not hinder our exclusive focus on reliability for the purpose of this study, one should not forget that achieving technical reliability is not the only goal in practice. There are trade-offs between performance criteria that policy makers need to keep in mind; primarily pursuing reliability may adversely affect the meeting of other performance criteria. Moreover, reliability cannot be sought at all costs; trying to be 100% reliable is not only very expensive, but is also likely to be impossible. This consideration needs to be kept in mind when we discuss the practical benefits of the proposed framework in chapter 8.

Second, the degree of coherence is a rather vague concept. How to measure coherence degrees and relate them to performance, especially in the face of possible trade-offs? What about low levels of coherence, or incoherence, and their effect on performance? Regarding the former, measuring coherence is indeed difficult beyond the two central / decentral ideal-types and yes/no answers. Fortunately, we may ignore this problem in this research because it aims to align organization with technical specificities to ensure reliability and does not compare the dimensions for the purpose of establishing the degree of coherence and overall performance. Regarding the latter, in his research on modernization in electricity networks, Jonker (2010) elaborates on the relationship between coherence and performance on the one hand and incoherence and innovation on the other. He argues that while higher degrees of coherence lead to better system performance, much in the way that others depict the actors and factors of tightly coupled systems to be better attuned to each other, lower levels of coherence (or incoherence) could lead to catastrophic failure and in turn would spur innovation in either the technical or organizational dimension (or both) in order to reestablish coherence (performance). Though this research does not aim to study the effects of incoherence, but tries to prevent it from happening altogether, for the sake of maintaining reliability in the face of technical changes, the notion of incoherence does have an important signaling function. It reminds us of the consequences of failing to align organizations to technologies beyond that of lower reliability. If for example, it would at some point prove difficult to maintain reliability in our roadmap towards hydrogen, because a technical change from onsite networks to the use of pipelines requires a more centralized control scheme that proves unpopular with the existing entities, innovations to reestablish coherence may very well take the roadmap into a different direction than intended by policy makers.

Third, coherence is rather simplistic. It is essentially based on two ideal-types of coordination mechanisms, centralized and decentralized, though one might extend them to the four levels of centralized operation and four levels of hierarchical organization. Things become problematic, however, when coordination mechanisms fit in between, i.e. are a mix of these ideal-types. How to utilize the concept of coherence on them? We need a framework that can provide more nuance and that can, in a scientifically justifiable way, relate technical characteristics of networks to organizational structures.

2.3 Maintaining Reliability in Socio-Technical Systems

The overview of energy infrastructures as socio-technical systems has clarified the technical and organizational dimensions and given us a first idea how to relate both dimensions with one another. Let us briefly recapitulate. Technically, energy infrastructures are technical systems composed of various components or entities, themselves comprising numerous individual assets, that operate in a certain order to facilitate system complementarity and that employ control mechanisms to ensure system integrity. Thus, from a technical perspective, maintaining reliability is all about ensuring the proper functioning of assets and control mechanisms on the one hand and meeting operational responsibilities and coordination requirements on the other. Socially, organizational structures, themselves a manifestation of entities' interests and the broader institutional setting, shape the division of responsibilities among entities and enable and constrain certain forms of entity interaction. Hence, from an organizational perspective, maintaining reliability is all about how entities' responsibilities are defined and how they may interact to coordinate for control. Finally, the concept of coherence focused attention on the linkages between both dimensions and their effect on infrastructure performance (which includes reliability). Yet whereas the necessity of matching the operational responsibilities and coordination requirements of entities with the organizational structures' division of responsibilities and coordination possibilities among entities for the sake of reliability became clear, an ability to systematically move from energy systems' technical and operational characteristics to their required organizational structures remains lacking. This can be caught graphically:

Figure 2.3 The role of coherence in the reliability of socio-technical systems

Keeping these insights from the perspective on energy infrastructures as socio-technical systems in mind, it is safe to state that maintaining reliability in socio-technical systems rests on two pillars (see Figure 2.4). First, ensuring the adequate functioning and maintenance of the technical assets involved. Second, ensuring that there is a degree of coherence between the (technical) operational responsibilities and coordination requirements of entities on the one hand and the organizational structures' division of responsibilities and coordination possibilities among entities on the other.

Figure 2.4 Maintaining reliability in socio-technical systems

From this perspective, three main challenges stand in the way of pursuing reliability, each of which could fill an entire research project if addressed in-depth. First, how to ensure the adequate functioning of technical assets? Second, what organizational structure is required for the reliable operation of a particular set of infrastructure technologies? Third, how to achieve a co-development of the technical and organizational dimensions (in order to maintain coherence among them)? While this research focuses on addressing the second question, let us briefly elaborate all three here to illustrate the overall challenge facing scholars, policy makers, and sector entities alike.

Ensuring the functioning of technical assets basically implies addressing the aforementioned typical failures in pipelines, wires, pressure stations, generation plants, etc. that are caused by natural disasters, human errors (by users and network companies), wear and tear, (lack of) maintenance, insufficient or incorrect use of network capacity, and lack of flexibility to respond to demand fluctuations. This involves efforts by infrastructure entities to install, monitor, maintain, repair, and replace technical assets when needed and by policy makers to set the right incentive structure for entities to do so in a liberalized environment through regulation and investment and innovation policies. Scholars can also contribute by developing more durable and robust materials. The technical functioning of assets is a well-known issue in the energy sector, but not always well-addressed, especially since liberalization caused the priorities of sector incumbents to shift towards making profit at the expense of adequate investment in the physical infrastructure.

Next, while the overview of energy infrastructures as socio-technical systems helps us to better understand the problem mentioned at the end of section 2.1 and shows us how we might relate the technical and organizational dimensions, we still have not yet addressed how to bridge the gap between the infrastructure operations and organizational structures, i.e. how to know what the organizational requirements of the technical characteristics of energy infrastructures in light of reliability are? Why does the operation of certain energy infrastructures require hierarchical organization and top-down control and others not; what aspects of technical operation might account for that? Of course, without a way to match both dimensions, how is one to align organization to technologies (or know coherence when you see it for that matter)? Which mechanisms or guidelines might we employ to responsibly move from technical characteristics of energy systems to their organizational requirements? This is the core question this research poses and it will be addressed in chapter 4.

Finally, even if we do manage to bridge the gap, maintaining reliability is no easy task. It is questionable in how far scientists, policy makers, and sector incumbents are able to achieve or how they may facilitate the co-development of infrastructure technologies and organization. Two main challenges need to be addressed.

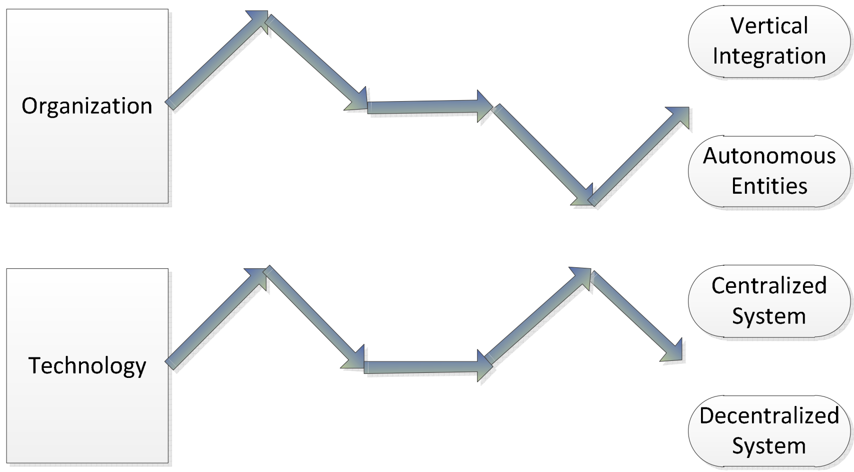
First, despite their robust and stable image, energy infrastructures in fact constantly undergo technical changes. Whether it is to enhance efficiency, increase capacity, adapt to new circumstances, or extend into new areas, physical networks are in motion throughout the life of infrastructures. Moreover, technical innovation is often desired and supported by policy. To ensure reliability in the face of these changes, however, demands great organizational flexibility of these networks. Detailed historical accounts of various infrastructures have shown time and again how technical changes may require a different approach to the governance of the networks they change (as we will see in the next chapter). The question needs to be posed whether organization can keep up. Yet at the same time, changes in infrastructure technologies need not necessitate organizational change. More incremental innovations, i.e. adaptations that optimize specific assets, may function just as well under the existing organizational structure. More radical innovations may, however, reshape network operations and may even initiate the birth of new infrastructures. Hence one also needs to address when new technologies may require a rethinking of organization and actor interaction.

Second, sector organization is the result of a complex mix of continuously shifting considerations. A wide variety of technical, economic, social, cultural, and political pressures influences actor behavior, the nature of actors (private or public) involved in the infrastructure, and the institutional setting in which they operate and which may define their interests. For example, concerns regarding profits and costs are weighed against certain public service obligations such as non-discriminatory access, service quality, and environmental neutrality, but also concerns of national security. In this complex setting, what ensures alignment to technical considerations, i.e. the optimization of organization to technical reliability concerns vis-à-vis other considerations? Historical accounts of infrastructure governance and organization show that political and economic concerns frequently shape sector organization while ignoring technical concerns (as we will see in the next chapter). The liberalization and privatization of the last decades may be considered a recent example. Hence, organization and technologies do not necessarily evolve by themselves in a way that leads to a coherent outcome; despite their interaction, both change in accordance to different environments. The questions then become under what conditions organization responds to technical demands rather than political or economic forces and what role governments and sector entities may play therein; i.e. how can they guide these processes towards coherence?

As a consequence of these challenges, developments in technologies and organization may either increase coherence, decrease coherence, or lead to no noticeable change. If we take a look at Figure 2.5 below, we can distinguish between various technical and organizational developments (illustrated by the arrows that depict movements between more or less centralization and hierarchy) and their effect on coherence. In the first two phases, the developments of technologies and organizational structures produce a similar effect in terms of reorientation. Both first centralize and then become more decentralized in nature. As such, assuming that we have a coherent infrastructure at the start, coherence is maintained throughout the process. This also holds true for the third phase, in which no noticeable change occurs. However, phase four shows a different and troublesome possibility:

incoherence. Where organizational developments drive the organization of the infrastructure towards a more decentralized structure, because of, for example, liberalization paired with unbundling, technological developments drive the coordination requirements of the technical system towards central control, because of, for example, increasing economies of system. Consequently, we see incoherence increase in phase four. Phase five in turn shows that opposite developments may also lead to increasing coherence.

Figure 2.5 Maintaining coherence over time



In the end, ensuring coherence is all about preventing developments from effecting the outcome of phase four, proactively supporting developments leading to coherence as in phase five, and monitoring developments throughout. Unfortunately, the many possible developments in both dimensions are nearly infinite, constantly reshaping what level of centralization and degree of vertical integration would represent coherence. The continuous readjustments required to maintain coherence, in turn, raise the complexity of achieving it to unmanageable heights. It seems fair to conclude that suboptimal results are the best we may hope for. It also creates confusion as to what to align to what: organization to technologies or technologies to organization? This also points to questions regarding how lock-ins and path dependencies of both a technical and organizational nature may affect each other and co-development. This will be briefly addressed in the concluding chapter, where we will discuss the challenges of executing a techno-organizational roadmap towards hydrogen in order to maintain reliability.

2.4 Conclusion

This chapter presented the conceptual starting point for maintaining reliability in energy infrastructures. It started by defining reliability as "the ability of the system to deliver the product (or service) transported over the network without interruption and without deterioration of its quality" (CPB 2004, 18) and highlighted the recent focus in literature on organizational causes for energy system failures and the difficulty in determining the organizational requirements of infrastructure operations. Subsequently, it presented energy industries as socio-technical systems in which supply chain components and their technical artifacts were identified as the technical dimension and the actors and institutions as the social dimension. It then proceeded by highlighting the crucial link between the operational responsibilities and coordination requirements of entities on the one hand and the organizational structure's division of responsibilities and coordination possibilities among entities on the other for the maintenance of coherence between both dimensions and infrastructure reliability. However, we also noted that despite these insights, we still lack the ability to systematically move from energy systems' technical and operational characteristics to their organizational requirements. As such, we had to acknowledge that while both dimensions of socio-technical systems are well understood, the relationship between them is not. This reemphasized the point of departure in this research; that the technical reliability of energy infrastructures has organizational requirements, yet that these are difficult to determine. At the end, the chapter pointed to the three possible directions for further research into maintaining reliability in socio-technical systems: a) how to ensure technical assets' adequate functioning; b) how to know what organizational structures are required for reliable operations; c) how to ensure that both dimensions co-develop? This research focuses on the second direction. The next chapter completes the problem setting by introducing the energy transition as a specific challenge to reliability; it implies technical changes to energy infrastructures that require a degree of coherence between its organization and technologies. It also presents the perspective taken in this research: how to align organizational structures to technologies (and not vice versa).

3. The Challenge of a Transition to Renewable Energy Systems

The consequences of a transition from fossil fuel based energy infrastructures to sustainable energy systems for the organizational requirements for the reliable operation of these systems are difficult to foresee. Which energy sources and carriers might be developed, how will they be produced and transported, what applications will they fuel, and how should they be operated? Fortunately, experiences from past energy transitions, the literature on socio-technical transitions, insights from the fields of infrastructure and network development, and accounts of changes in energy sector governance and organization together present an elaborate overview of what one may expect in terms of the transition process and the technical and organizational changes therein. In this light, this chapter addresses the sub-question: what may a transition to renewable energy systems imply in terms of technical and organizational changes in energy infrastructures? Its aim is twofold. First, to increase our understanding of what an energy transition implies with regard to reliability: a series of technical changes that may or may not require changes in organization to ensure technical functioning. Second, to discern general patterns in the technical and organizational changes (and their relationship) during the development of infrastructures.

3.1 The Energy Transition as Challenge to Infrastructure Reliability

Increasing fossil fuel scarcity and deteriorating environmental conditions call for a transition towards a more sustainable energy system (Dorian et al. 2006; Rifkin 2002). On the one hand, from a political economic perspective, the current energy market is facing a situation of demand-induced, supply-induced, and structural scarcity, or a combination thereof (Amineh and Guang 2010, 6). "Demand-induced scarcity refers to a situation in which population growth, a rising per capita income resulting in higher levels of consumption, and technological change that renders fossil fuels more essential for the production of wealth and power, increase domestic demand for fossil fuels" (Amineh and Guang 2010, 6). For example, the growth of the global population and industrialization of developing countries such as China and India, has led to a rapid increase in global energy demand (Dorian et al. 2006). "Supply-induced scarcity refers to a situation in which a decrease of stock (or market-efficient access to it), inefficient use of supplies, and a lack of adequate productive capacity and pipeline infrastructure, decrease the supply of energy resources" (Amineh and Guang 2010, 6). Decreasing oil and natural gas reserves (British Petroleum (2011a, 2011b) and the costly exploitation of tar sands for producing oil are a case in point. Combined with increasingly volatile energy prices due to peak oil expectations, unstable financial markets, and geopolitical tensions in oil and gas producing regions and countries, energy supply security is not a given.[49] "Structural scarcity refers to a situation in

[49] The stock market price for a barrel of oil was rather volatile in recent years; it especially fluctuated between its record price of 147$ in the summer of 2008 (due to expected scarcity)

which there is a supply-induced scarcity caused by the deliberate action of a major power or non-state actors, such as transnational oil companies" (Amineh and Guang 2010, 6).[50] For example, a major power may opt to hinder the transportation of energy between two countries, the global community may pose international sanctions on a producer, or countries may form cartels like OPEC. On the other hand, from an environmental perspective the burning of fossil fuels such as oil, coal, and natural gas leads to "CO2-emissions, the exhausting of resources, local environmental degradation and climate change" (Criekemans 2011, 4). Though still disputed by some, the general consensus among scholars is that CO2 emissions from the burning of fossil fuels lead to global warming and climate change that could drastically alter our natural habitats and agriculture. Possibilities for carbon capture and storage might remedy this, but are costly and some concerns about the underground storage of CO2 on the local environment remain. Moreover, local pollution near refineries might be immense, as Nigeria and the oil spills in the Gulf of Mexico have shown. The combination of all of these factors present clear and simple reasons for developing renewable energy sources and carriers.

According to the International Energy Agency (IEA) "[r]enewable energy is energy that is derived from natural processes that are replenished constantly [and includes such sources as] solar, wind, biomass, geothermal [and heat], hydropower, ocean resources [tidal and wave], and biofuels, and electricity and hydrogen derived from those renewable resources" (IEA 2004, 12).[51] The defining aspect of renewables is that they are 'renewable', i.e. that "they replenish themselves in a natural way" (Criekemans 2011, 6). Renewable energy sources hence stand in contrast to conventional, exhaustive energy sources such as coal, oil, and natural gas. An important feature of renewables is that they are 'flow limited'; for example, the sun does not always shine with the same intensity, the wind does not blow constantly, etc. This creates challenges for balancing electricity grids and meeting consumption peaks; what if there is no wind during dinner time to fuel the stove? The concept 'renewable' should not be confused with sustainable. "Sustainable development can in general be described as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Criekemans 2011, 7; World Commission on Environment and Development (Brundtland Commission) 1987). Most renewable sources are sustainable, but this is not always the case. Biomass (such as wood) and bio-waste might be replenishable, but the burning of it still releases

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and the consequences of the financial crisis a few months later (with the result that investment in renewables also plunged (Criekemans 2011, 4-5).

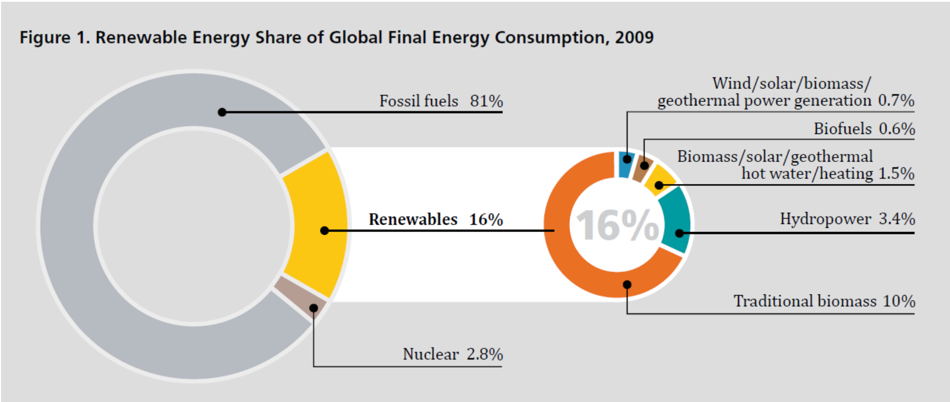
[50] That option, however, is usually available "only after oil and gas have been brought to ports and ships from the territory of extraction" (Amineh and Guang 2010, 6).

[51] To compare, the U.S. Energy Information Agency (EIA) defines renewable energy sources as "Energy sources that are naturally replenishing but flow limited. They are virtually inexhaustible in duration but limited in the amount of energy that is available per unit of time. Renewable energy sources include: biomass, hydro, geothermal, solar, wind, ocean thermal, wave action and tidal action" (Criekemans 2011, 6). The EU defines renewable energy sources as "All natural energy flows that are inexhaustible (i.e., renewable) from an anthropogenic point of view: solar radiation; hydropower; wind; geothermal; wave, and tidal energy; and biomass" (Criekemans 2011, 6).

CO_2. Similarly, hydropower might be based on replenishable water supplies, but the damages to surrounding agricultural land or local flora and fauna raise questions as to how sustainable it really is. Another matter is the relativity of the concept of replenishable. While solar radiation and wind are constantly renewed, biomass consumption might come to outgrow its production. In a way, even fossil fuels might be considered renewable if consumption would be so low that a few million years is enough time for them to replenish. In any case, this research considers the IEA definition and the renewable energy sources and carriers in it as renewable. Moreover, the term 'sustainable' is used throughout this research in reference to renewable energy sources and carriers.

A transition to renewables, then, implies moving from a fossil fuel based energy system to one based on renewable energy sources and carriers and supporting technologies. This replacement is said to take place in four distinct areas: power generation, stand-alone systems, household heating, and transportation. A wide variety of renewable and alternative energy possibilities exist to replace, even if only partially until 2050, the three currently dominant energy vectors of oil, natural gas, and electricity (coal, nuclear or otherwise): solar photovoltaic (PV), solar heat, wind, hydropower, tidal, wave, geothermal, waste, biomass, biofuels, and hydrogen – with many experimental renewable technologies in earlier stages of development. The various renewable energy sources and carriers and supporting technologies are being explored in futuristic visions and roadmaps thereunto and in concrete experiments and demonstration projects (see the IEA and REN21 websites for an overview of (country) efforts). So far, however, renewable energy still remains a marginal contributor to global primary energy and electricity supply, despite rapid increases in installed capacity and investment in the last decade. As Figure 3.1 shows, without large-scale hydropower and traditional biomass, the share of renewables in global final energy consumption is very small; renewables like small hydro, modern biomass, wind, solar, geothermal, and biofuels accounted for a mere 2.8% (REN21 2011, 17). Leaving out hydropower, the share of renewables in global electricity generation in 2010 stands at a similar 3.3% (REN21 2011, 18). In stark contrast to the low share of renewable energy in the global energy mix stands the growth in installed capacity of and investment in renewables. Between 2000 and 2008, renewable energy based electricity power stations (excluding hydropower) "have more than tripled at a global scale according to the American National Renewable Energy Laboratory (NREL 2008, 43-45). Moreover, the World Energy Outlook 2009 of the IEA states that global investments in new renewable energy-generating assets or capacity have risen enormously in the last years (IEA 2010, 161-162). These trends are likely to continue if one considers the falling costs of renewable electricity generation vis-à-vis fossil fuel based generation (Cowan and Daim 2009, 337). The growing role and urgency for renewable energy is also demonstrated by the founding of the International Renewable Energy Agency (IRENA) in 2009, an intergovernmental organization tasked with promoting worldwide renewable energy adoption.

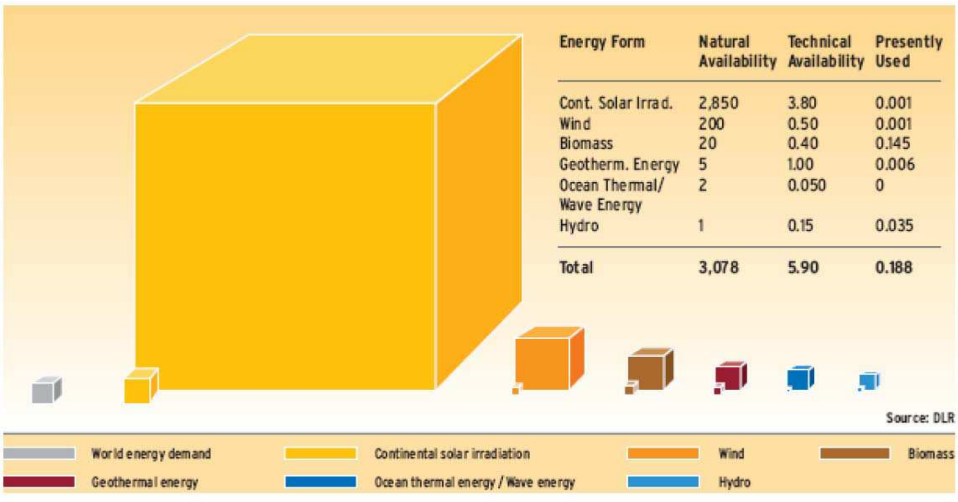
Figure 3.1 Share of renewable energy sources in the global energy mix in 2008



Source: REN21 2011, 17.

The combination of the small share in global primary energy supply and recent investment in renewables shows that countries and firms are only just beginning to exploit renewable energy sources. This view is emphasized by the fact that "current technologies in renewable energy only capture a fraction of the available solar energy, wind energy, biomass, geothermal energy, ocean thermal energy, wave energy and hydropower" (Criekemans 2011, 23). Hence there is much untouched potential remaining.

Figure 3.2 Potential global energy supply based on full exploitation of renewables



Energy Form	Natural Availability	Technical Availability	Presently Used
Cont. Solar Irrad.	2,850	3.80	0.001
Wind	200	0.50	0.001
Biomass	20	0.40	0.145
Geotherm. Energy	5	1.00	0.006
Ocean Thermal/ Wave Energy	2	0.050	0
Hydro	1	0.15	0.035
Total	3,078	5.90	0.188

Source: Criekemans 2011, 23.

The introduction of renewable energy sources and carriers necessitates the development of new supporting technologies and may reshape infrastructures. Let us briefly take a look at solar, wind, and hydrogen renewable energy systems to illustrate some possible changes they might imply in terms of the operation and organization of existing energy sectors.

A prominent new renewable energy source is the use of solar PV for electricity generation by households.[52] This not only enables households to produce electricity themselves for domestic use and save money in the long term, but also allows households to feed electricity into the grid and for remote locations to be self-sufficient. Technically, solar panels transform solar radiation (sunlight) into electricity which then passes through a charge controller and battery tanks before being transformed from direct current (DC) to alternating current (AC) current by an inverter (PTL Solar 2011). It may then be used as electricity for household appliances such as lights, cooking, etc. Alternatively, the AC current may be fed into the electricity grid, i.e. selling the produced energy to other consumers and using the utility companies' existing grid for transportation. In that case, metering becomes an important aspect since domestically produced electricity needs to be deducted from the energy bill, which itself might be negative if the household generates more solar energy than it uses.

The possibility that households might start to produce more electricity than they consume, creating a surplus that they could sell to other household or industry customers, creates a serious challenge for electricity grid operations.[53] Such energy-producing consumers, or 'prosumers' (UCP 2010, 38), create some important implications for local distribution and likely, in turn, for transmission networks. Please remember that traditionally, the distribution network "was designed and built as a one-way conductor for energy to end users" (UCP 2010, 45). Are distribution companies able to manage bi-directional energy flows?[54] Another question is who should manage the new electricity flows and energy systems of the future. Developments in IT "could eventually make it possible for consumers to send their excess in produced solar energy *peer to peer* to other consumers across the grid" (Criekemans 2011, 10), hollowing out the role network companies may play in directing energy flows. To realize such a development, it would be necessary to "install 'smart meters' which have the capacity to detect instantly who has excess

[52] Solar PV may also be used to generate heat for household heating.

[53] The production of gas from biomass and/or waste is considered to be of a lesser extent.

[54] "This leads to the following market considerations: it all begins with the position for the end customer whose market is moving from a supplier market model (in which the energy company decides what to offer) to a demand type model (in which the end customer determines the propositions)" (UCP 2010, 51). "The expected trends in the energy sector will cause a paradigm shift. These trends will primarily concern the entities DSO, Metering and Retail and will change both technical functions and commercial functions. As a result of this we will see a convergence in the technical functions operated by the TSOs and DSOs" (UCP 2010, 54).

capacity and who does not" (Criekemans 2011, 10). In addition, billing methods, now mostly based on fixed monthly payments and end-of-the-year reconciliations, would also require such smart meters and need to change towards frequent financial settlements that incorporate electricity feed-in based on up-to-date accurate data (UCP 2010, 37). A different effect from decentral production and consumption of renewable energy by households is that it allows "local and regional groups [to] organise themselves more independently [from] central energy companies as was the case in the conventional energy regime" (Criekemans 2011, 10). Moreover, increasing electrification also has impacts on competitive energy sources such as natural gas. In the end, a system where households are no longer mere consumers of centrally generated electricity transported to homes by utility companies, but where they rather operate as producers, is likely to require a very different way of organizing distribution networks (see also Malik 2000).

Another prominent new renewable energy source is wind farms, either onshore or offshore. In terms of set-up, wind farms are very similar to central electricity production and distribution. Wind farms comprise multiple turbines that are placed in one location and whose generated electricity passes through a control center before being added to the transmission grid via a power substation. The farm and control center together basically act as a power plant. The current electricity supply chain is thus hardly different from both a technical and operational perspective, be it that another producer is added to it and the intermittent nature of wind electricity generation. Currently, most modern wind turbines generate between 600kW to 5MW, though most commercial use is in the range of 1.5 to 3 MW. Efficiency depends greatly on wind speed and constant flow, making high altitudes and seas ideal locations. Due to their size, 'not in my backyard' concerns have been known to hinder the deployment of wind farms and may be expected to hinder future deployment now that many convenient locations are already occupied. Of course, decentral wind power generation is also possible, but is often only considered as a small hybrid electric system that combines wind and solar PV technologies. This offers one major advantage over either single system; because solar energy is plentiful in summer when sunshine is brightest and longest and wind energy is more plentiful in winter when wind speeds are strong, there is the possibility to secure a more constant energy supply. Such "hybrid systems are stand-alone systems, which operate 'off-grid'" and are supported by batteries and/or diesel engine generators for emergency back-ups (energysavers 2011).

The possibility to produce wind energy centrally and decentrally and to use it in conjunction with other renewable energy systems points to another challenge in assessing organizational requirements of renewables: what to prepare for? Renewable energy can come from both "large energy corporations and structured in the classical centralised, top-down and supply driven format", and "local and regional facilities [that] fulfil their own demand and sell the balance to the market", i.e. central or decentral facilities (UCP 2010, 71). Generally, a central approach is deemed preferable when "facilities are physically large, geographically remote from user centres, require large investments and provide relatively high risks" (UCP 2010, 71). Alternatively, a decentral approach is deemed preferable when "facilities are physically medium to small, can be located near and are directly connected to users and require limited investments with equally limited risks" (UCP 2010, 71). Typical examples of central renewable energy sources and carriers are hydropower and waste incineration. Hydropower is geologically bound to the location of lakes and rivers in generally mountainous areas; although it may occasionally be produced from smaller rivers, the production levels required for national electricity supply can only be met by large central hydropower facilities. Similarly, waste incineration requires "a certain scale in waste collection and operation to perform efficiently" (UCP 2010, 72). Typical examples of decentral technologies are solar PV[55] and biofuel CHP systems. The use of solar panels on roofs is the easiest manner in which the unproductive surfaces in urban areas can be utilized for power generation. Of course, solar farms may exist as well, as the Desertec project in North Africa and the Middle East shows, but the bulk of solar energy applications seems determined for decentral generation. Finally, wind energy seems to fall somewhere in between. On the one hand, "wind power started out as a decentral technology", with 'local rural communities and farmers […] usually the first to adopt this technology" (UCP 2010, 72). With the increasing scarcity of suitable locations for wind turbines due to their increased numbers, however, "together with allowing wind turbines to grow to MW proportions […] wind turbines became 'big iron' and therefore the domain of specialised wind project companies and energy corporations" (UCP 2010, 72). An example is the *North Sea Offshore Grid Initiative*, "a complex of thousands of windmills in the North Sea" (Criekemans 2011, 11). These distinctions in the scale of deployment are also a matter of preference by policy makers in various countries. Whereas France seems to favour big projects operated in a rather centralized way, Nordic countries are known for their distributed means, with the Netherlands being somewhere in between (Criekemans 2011, 12). In the end, a thorough blueprint seems of great value in pinpointing the technical composition of future energy systems and the ability to prepare for their organization.

A somewhat different example of a future renewable energy system is using hydrogen as an energy carrier for stationary and mobile applications. Currently, energy is transported as oil, natural gas, or electricity. In principle, hydrogen could replace oil and gas. The advantages would be that hydrogen is very versatile; it can be produced from all fossil and renewable sources, it can be transformed into electricity and back, it can be transported via truck and pipeline, and it can be stored. Consequently, most future uses of hydrogen as an energy carrier paint a very ambitious picture of the hydrogen system (Altenergymag 2011). The disadvantages, of course, would lie in an additional step for conversion and its accompanying energy efficiency loss, the need to install fuel cells, and most importantly the building of hydrogen production, transport, and storage means. Obviously, such a shift towards hydrogen would imply major technical changes. Yet it remains to be seen in how far this will be translated into organizational changes. The operation of a hydrogen pipeline system might involve different technologies than a natural gas based pipeline system, but the coordination of operation among entities involved might not fundamentally differ.

[55] "Technological developments such as thin film solar material and ongoing architectural integration of solar technology in new houses and buildings makes solar technology a typical decentral phenomenon" (UCP 2010, 72).

The challenge of a transition to hydrogen, besides its scale and actual execution, lies in its versatility and long duration. First, hydrogen's versatility can hinder the pursuit of a clear goal or formulation of a desirable end-state hydrogen economy. Second, the transition from fossil energy to renewables is not likely to happen overnight. Many intermediate stages may develop during the transition, each harboring its own set of technologies and organization requirements. In other words, an energy transition implies a series of technical changes over an extended period of time. For example, hydrogen networks might first be based on onsite production to stimulate demand, whereas later they might require pipelines to transport greater volumes. Consequently, infrastructure organization may be subject to continuous recalibration to keep up with changing technologies. Thus the complementary organizational structure for a particular energy source or carriers' infrastructure may be constantly changing. Besides the question in how far policy makers and sector entities are able and willing to continuously restructure organization for the sake of maintaining reliability, of which one should be very sceptical, such a dynamic process is sure to raise its own challenges. In any case, some rough visions of future energy systems are inadequate; detailed technical roadmaps are necessary to prepare for the series of technical changes that represent the build-up of energy systems.

As if the development of a variety of renewable energy technologies is not complex enough, it is accompanied by the possibilities that ICT and/or smart-grids may offer (Bouffard and Kirschen 2008). Developments in information technology (ICT) enable new possibilities for networks: moving from mono- to multi-gas grids, from uni- to bi-directional flows, from 'passive' to smart grids, and dealing with the increased complexity of networks. Especially the smart-grid technology is likely to have major implications for the way in which energy networks are run, especially for distribution networks (Bolton and Foxon 2011). Smart grid concepts for example create the possibility for network companies to actively balance "demand and supply at lower grid levels using information and communication techniques (so-called local balancing)" (UCP 2010, 115). As we saw in the previous chapter, traditionally networks were hierarchically structured, with a central role for the TSO in gathering demand and supply data and monitoring and balancing the energy grid for stability. Information technology, coupled with distributed generation of renewable energy, may change this situation as generation, consumption, and storage are dynamically impacting the lower network grids. In turn, "network companies will become more and more responsible for balancing their regional and local grids" (UCP 2010, 116-117). As a consequence of such a development, the role of the current distribution companies would become less that of a traditional network company and more that of a distribution system operator (DSO).[56] Additionally, where "central coordination mechanisms are lacking, making way for distributed control strategies, infrastructures

[56] "Whereas the DSO often refers to a regional role, some also call the future network company a Local Systems Operator (LSO) that manages micro grids. A DSO is expected to be a regulated network company. An LSO could very well be non-regulated as micro grids that connect small residential areas or business parks will increasingly be privately owned and operated in a local-for-local manner" (UCP 2010, 117).

might be equipped with self-organising and self-healing properties, so as to deal intelligently with disturbances and recover more effectively from incidents" (Weijnen and Bouwmans 2006, 129). Due to this increasing merger of energy and technology, some already speak of an 'energy-technology revolution' (Criekemans 2001, 9).

To sum up, a transition to a renewable energy system implies more than a simple replacement of one energy source by another. Technically, such a transition may disassemble and reassemble an infrastructure from sources and production facilities to transmission, distribution and storage means and on to end-use applications. Organizationally, different degrees of centralized control and hierarchical organization might be required to facilitate technical functioning. The challenge in this regard is to understand when technical changes caused by the introduction of renewable energy sources or carriers may require new networks and organizational changes and when not. The examples above already show that the addition of renewable energy technologies may have very different effects on the composition of current and future energy systems and their operation. While hydrogen, for example, would require own production sites and pipelines or trucks for delivery, solar or wind energy would require new solar panels and wind parks (production sites) but may utilize the existing electricity grid for transport, because only larger amounts are likely to require new transport capacity. In other words, some changes may remain limited to changing an artefact or energy chain component while others require a change of several infrastructure components, or even the building of a new infrastructure. In case of the latter, the roles and responsibilities of the entities involved in the daily operation of an infrastructure may change. For example, while it may be easy for electricity producers to add renewable energy to their portfolio (the more so because the use of the electricity grid remains the same), replacing oil based vehicles with electric or hydrogen vehicles, even when automobile manufacturers remain the same, requires different means of distribution and may invite newcomers to compete with incumbent distributors. Some of these technical changes could imply very different tasks for DSOs, TSOs, producers, etc. (as we saw with the prosumers and smart-grids above) and presents a serious challenge for the coordination of the activities of the various actors in these future infrastructures. The leading argumentation and decisive factor in this regard seems to be that while new (renewable) energy and infrastructure technologies may alter technical components, as long as they don't alter the responsibilities of components (the who does what, when, and how) and the coordination relationship between them, the organizational structure need not change.

In the end, the transition to sustainability poses a specific challenge for the maintenance of reliability in energy infrastructures; it implies a series of technical changes in infrastructure systems whose reliability requires a degree of coherence between its organization and operation.[57] The question then becomes what the

[57] Identifying the challenge of an energy transition in this fashion signals the specific perspective followed in this research; it is the organization that needs to be aligned with technology. The opposite, that technologies can be brought in alignment with the institutional dimension, is not investigated. This research basically takes a "what if"-perspective: what if a transition to a sustainable energy system would be or is being carried out, and the technical

technical changes stemming from the introduction of renewable energy sources and carriers may imply for the organization of energy infrastructures. What organizational structures do new energy technologies require to reestablish the coherence necessary for system reliability? This is difficult to say. Besides the absence of a framework for alignment, the variety and nuances in technical changes pose considerable obstacles to even the most careful of educated guesses. This brings us to the core challenge of this research: how to establish when new technologies require a rethinking of organization? This will be addressed in chapter 4. For now, let us first look at some experiences from past energy transitions to help discover some heuristics of what we may expect for the transition to renewable energy and the accompanying development of infrastructures.

3.2 Energy Transitions and Patterns in Infrastructure Development

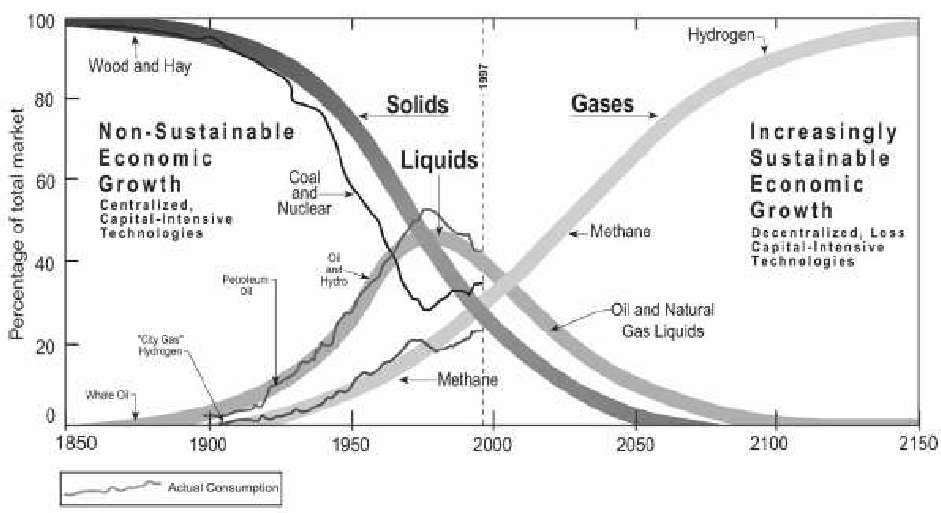
The transition to a renewable energy system is not the first transition from one form of energy to another. Since the 19th century, shifts from wood to coal to oil to natural gas have preceded it, as has the introduction of electricity. These alterations basically represent shifts from solid to liquid to gaseous energy sources, from less to more concentrated energy sources (in terms of their carbon-hydrogen atoms ratio) and towards increasingly economically lucrative and transport efficient energy sources. For example, energy from wood was the main source until the middle of the 19th century all over the world. When population density and energy use were growing rapidly in certain places, as in Great Britain, "wood began to lose out to coal, an energy source that was as abundant as wood but more concentrated, and not as bulky or awkward to transport" (Dunn 2002, 238). Similarly, while coal was the dominant energy source well into the 20th century, "energy system[s] based on fluids, rather than solids, began to emerge as the transportation system started to shift away from railroads and toward automobiles" (Dunn 2002, 238). Coal now found itself challenged, due to its weight and volume, by oil, "which featured a higher energy density and an ability to flow through pipelines and into tanks" (Dunn 2002, 238). By the mid-20th century, oil became the world's leading energy source. Currently, oil is being challenged by natural gas, the fastest-growing fossil fuel (overtaking coal in 1999) and the fuel most used to produce electricity. "Despite improvements from wellhead to gasoline pump [, n]atural gas, in addition to being cleaner and lighter and burning more efficiently, can be distributed through a network of pipes that is less conspicuous, more efficient, and more extensive than the one used for oil" (Dunn 2002, 238). In this light, the transition to sustainability is merely the next step.[58] However, it distinguishes itself

changes were progressing along the line of a specific roadmap, what would complementary organizational changes be with regard to maintaining reliability? In addition, this research does not investigate how best to ensure the reliable functioning of the technical assets as such. That is widely addressed in other literature and supported by a variety of well-established policy instruments (see chapter 2 and 8), even though they may not always be implemented successfully.

[58] These changes in energy sources present a disruptive picture of energy transition development, as each new energy source is replacing an old.er one Another perspective that

from earlier energy transitions by the lack of immediate economic benefits of switching to renewable energy sources and carriers and the environmental benefits that drive it.

Figure 3.3 Past energy transitions



Source: Dunn 2002, 239. For a similar account see Podobnik 1999, 157.

Considering these past shifts in energy sources, it is possible to study how these shifts have affected the technical and organizational dimensions of energy infrastructures and what we may expect for the transition to renewable energy systems. In other words, what can we learn from past experiences and what may we reasonably expect for the future? To study these matters, the literature on socio-technical transitions (Geels 2002 and 2004; Shackley and Green 2007), infrastructure development (Hughes 1983; Jackson et al. 2007; Ewertsson and Ingelstam 2004; Sawhney 2003), and energy sector governance (De Bruijne 2006; Verbong and van der Vleuten 2004; Millward 2004; Nightingale et al. 2003) prove useful. The first body of literature helps to understand the general transition process of socio-technical systems without going

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can be taken to discuss the same events is that of a continuous decarbonization. "From wood to coal to oil to natural gas, the ratio of hydrogen (H) to carbon (C) in the molecule of each successive source has increased" (Dunn 2002, 238-239). Where this ratio was between 1-3 and 1-10 for wood, it became 1-2 for coal, 2-1 for oil (LPG being 8-3), and finally 4-1 for natural gas (methane). If we follow this decarbonization-trend, the next logical fuel in this progression is hydrogen, containing two hydrogen and no carbon atoms. A word of caution is in order, though, considering that the 'trend' does not seem to distinguish energy carriers from energy sources. Whereas wood, coal, oil, and gas are energy sources, hydrogen is an energy carrier. Its production may involve carbon emissions, if produced from fossil sources. In addition, renewable electricity, or nuclear energy for that matter, does seem to fall into this trend as well, yet is not mentioned by Dunn.

into the details of any specific energy transition. The second provides a detailed description of how infrastructures generally develop from birth to maturity in a technical (and economic) sense, but does not specifically focus on energy infrastructures. The third presents an overview of energy infrastructure governance (and reliability) between 1850 and 2010, but does not do so per infrastructure. None of the three perspectives captures the whole picture or the exact information sought, yet the combination of them does a good job at portraying the most likely consequences of a transition to a renewable energy source for infrastructure development.[59]

A word of caution is in order at this point, however. While the three overviews highlight general patterns in the transition process, the technical en organizational development of energy infrastructures, and provides some guidance as to what to expect, we will see that it remains difficult to state anything with sufficient certainty about specific outcomes of energy transitions regarding infrastructure development. This is because energy transitions and infrastructure development are very case-specific experiences, making prediction a risky undertaking. For example, energy transitions are both cause and consequence of the environment in which they take place.[60] Put differently, transitions from one energy source to another often take place within a myriad of technical, economic, political, and cultural developments. The same holds true for the development of accompanying infrastructures. Consequently, the technical operation and organization differs greatly across countries and historical periods. Moreover, while past energy transitions by and large involved the development of new infrastructures that produced and transported the energy source to its users[61], this need not imply that new infrastructures are always required. We

[59] We consider this approach preferable to studying individual accounts of energy infrastructures for two reasons. First, we desire to have rough heuristics; studying individual accounts is too case-specific and studying many individual accounts is too time-consuming. Second, there simply seems to be no account that directly studies the relationship under study, i.e. no account seems to describe in an integrated fashion how infrastructures develop technically and operationally and how this has affected infrastructure organization. A likely reason for this is (as we will see below) that infrastructure organization is mostly driven by political and economic factors.

[60] For example, shifts in energy sources often coincide with larger revolutions in technology and industry. On the one hand, the technological innovations that triggered big industrial revolutions all seem to utilize new forms of energy. The machinery required for the first IR at the end of the 18th century signaled the switch from wood to coal and steam. The second IR at the end of the 19th century coincided with the shift to electricity and oil. Finally, the 3rd IR was simultaneous with the starting use of nuclear energy and purposeful use of renewables to limit pollution (Von Tunzelmann 2003, 371). On the other hand, new energy technologies may be linked to Kondratieff upswings. "The patterns of technological change and diffusion of innovations appear to be consistent with the hypothesis of long waves in economic development" (Grübler and Nakicenovic 1991, 314). Of course, this evidence is phenomenological; it is difficult to establish causality.

[61] For example, shifting from coal to oil to gas for example introduces very different transport means: from rail to trucks and pipelines to different pipelines. Electricity networks of course also required their own infrastructure. This is not only true for energy infrastructures either. Looking at the transport sector, shifts from shipping to railways to road trucks heralded big

already saw in section 3.1 that certain new renewable energy technologies might simply be added to existing networks.

3.2.1 The Transition to Renewable Energy Systems

Energy transitions, including the transition towards a renewable energy system, are often regarded as socio-technical transitions because they involve much more than technical changes only. They reflect "processes of socio-technical evolution in which economic, institutional and technological structures develop interactively and change drastically in the long run" (Bruggink 2005a, 6). This has led Geels, Rotmans, Kemp, Loorbach, and Verbong (2000-2010) to classify socio-technical transitions as societal transformation processes of an evolutionary nature lasting at least one generation (around twenty-five years). To understand socio-technical transitions, transition theory examines "how technology is shaped by social, economic, cultural and political forces as well as how new technologies shape society and the interaction between various actors" (Elzen et al. 2002, 11). It builds upon the discipline of science and technology studies and stresses the interrelation between technical innovation processes and their wider societal context.[62] Special attention goes to three 'levels' and the interactions among them: energy landscapes, socio-technical regimes and technological niches. Figure 3.4 captures these three levels and their interaction in one central model.

The core unit of analysis in transitions is the socio-technical regime. Socio-technical regimes consist of "a set of technologies embedded in a social, political, and institutional context with its associated regime-specific set of rules, procedures, habits and practices" (Shackley and Green 2007, 223).[63] Energy infrastructures are a good example of such socio-technical regimes, as they are often constructed around a core set of related technologies in order to function (e.g. a gas pipeline network), while they also necessitate rules of the game to ensure a certain level of performance in terms of, for example, efficiency and effectiveness, public values, and technical reliability. These rules of the game make up the formal and informal institutions that "structure political, economic and social interactions" and "set limits on human behavior" (North 1990). What makes the regime work, are the actors linking the various

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changes in how cargo was transported, making and braking whole cities and regions in the meantime.

[62] It needs to be remembered throughout this section, however, that the aim is not to facilitate an entire transition, as in the sense of transition management (Grin et al. 2010), but to focus on the matter of how new energy technologies may affect existing infrastructures and/or require the development of new infrastructures. Emphasis is hence not on 'getting there' in terms of the diffusion of renewable technologies, but on deriving general heuristics regarding changes in network operations and coordination throughout a transitional process.

[63] This conception differs from the definition of technological regimes that Nelson and Winter (1982) use because the rule-set incorporates a wider embeddedness than engineering communities only. Now, many social groups affect technical trajectories. This led Rip and Kemp to define a technological regime as "the rule-set or grammar embedded in a complex of engineering practices, production process technologies, product characteristics, skills and procedures, ways of handling relevant artefacts and persons, ways of defining problems; all of them embedded in institutions and infrastructures" (Elzen et al. 2002, 12-13).

technologies, markets and rules together. These can be technology suppliers (universities, R&D departments, and knowledge institutes), infrastructure entities (production, trade, transmission, storage, metering, distribution, and retail companies), government policy makers (federal, state, regional, and local authorities, regulatory agencies), and private actors (consumers, public and private organizations). A regime is dynamically stable; while the different technological, economic and institutional aspects are adjusted to each other, bringing stability, they are also constantly changing within the range or context of the regime.[64] However, the regime is quite inert to adapt to changes outside the discourse of the regime, hence the idea of system transition. This implies that changes within the regime are of a more incremental nature, whereas changes emerging outside of the regime force the creation of a new regime and hence have a more radical nature. Thus, it is at this level where "'lock-in' [and path-dependence] may take place" (Shackley and Green 2007, 223).

The technological niche is the level where "new technologies emerge and some develop, protected from the full effects of competition with the dominant technologies in the socio-technical regime" (Shackley and Green 2007, 224). Some examples are the military, industrial vehicles, or shipping. Niches are important for testing, on a small scale, the expenses, safety and reliability of innovations. They serve as incubators for radical novelties that have a "low technical performance, are often cumbersome and expensive" and operate under different performance indicators or selection criteria (Elzen et al. 2002, 13). Niches also create opportunities to construct social networks among (regime) actors that support specific innovations such as alternative and renewable energy technologies such as hydrogen. The literature on technical innovation systems has repeatedly pointed to the fact that even technologies in their earliest form may require certain institutions to be in place to operate and develop. Hence niches are often represented as niche-regimes.

The landscape level provides "the dominant assumptions, values and deeply rooted socio-economic trends at a given period of time" (Shackley and Green 2007, 222). This includes the key 'Weltanschauung' or philosophy behind policy-making and reflects "the dominant perception of 'problems' and the way to resolve those problems" (Shackley and Green 2007, 223). These belief systems change very slowly and are hence often considered as the constant external environment or structure in which the socio-technical regime operates but over which its actors have no direct control. To illustrate, "in our own society, the landscape is given by a concept of economic growth which has relied since the industrial revolution on fossil fuels, albeit with major shifts from coal, to oil and natural gas" (Shackley and Green 2007, 223). However, recently two trends have also started to shape the landscape level:

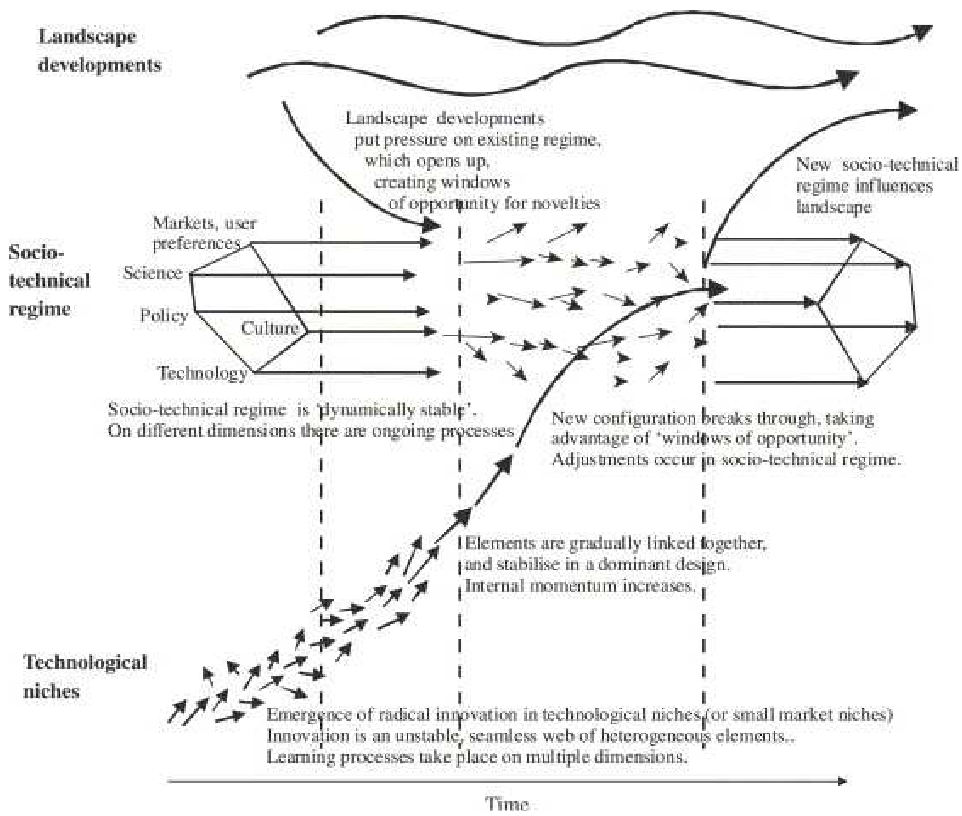
[64] The interrelations between these dimensions are the key to understanding the performance of the whole regime. Innovative technologies, institutional changes and changes in consumer demand, for example, can have profound impacts not only on their own dimension, but across the whole regime or infrastructure. Without the technical feasibility to allocate goods and services in physical networks, there can be no economic transaction. Moreover, infrastructures often involve market failures, necessitating institutional governance. Finally, without proper governance, technological functioning and economic performance will be sub-optimal.

institutional liberalization and increasing environmental awareness. Other important aspects are global fossil fuel scarcity and its geographical concentration, increasing energy demand, consumer preferences, demographic composition, level of urbanization, available technology, cultural characteristics, national specificities, etc. Changes at the landscape level can have profound impacts on the socio-technical regime as they can alter the rules of the game in which regime actors operate by changing the relevant goals and performance criteria and even by altering the perception of what is the appropriate or 'normal' way of doing things.

The relations among the three levels are characterized as one of a nested hierarchy. As such, niches are embedded in regimes and regimes in landscapes. Here, the socio-technical regime "accounts for stability of existing technological development and the occurrence of trajectories. The macro-level of landscape consists of slow changing external factors, providing gradients for the trajectories. The micro-level of niches accounts for the generation of radical innovations" (Elzen et al. 2002, 14). Within this context, innovation mostly occurs within the existing regime, and involves incremental changes towards regime optimization. This gradual pattern results from the interconnectivity of the various regime dimensions that allows only for small changes within the margins of the regime. However, "although gradual change is the common pattern, there are plenty of historical examples of more radical transitions" (Elzen et al. 2002, 14), e.g. the transitions from coal to oil and onto gas based energy systems.[65] Here, novelties emerge and are developed in niches under the old framework - existing regime and landscape - often facing a mismatch with the established socio-political dimensions (Freeman and Perez 1988). If so, new opportunities are typically countered by certain regime actors threatened by it. In the end, "it is the alignment of developments (successful processes within the niche reinforced by changes at regime level and at the level of the socio-technical landscape) which determine if a regime shift will occur" (Kemp et al. 2001, 277). This shows the importance of the complementarity of institutional and technical change for a successful transition.

[65] Our illustrative case, a transition to hydrogen as a motor fuel, also falls in this category.

Figure 3.4 The multi-level perspective on socio-technical transitions



Source: Shackley and Green 2007, 222. Based on Geels 2002, 1263 and Geels 2004, 915.

Studies on socio-technical transitions distinguish between a wide variety of transition processes (Geels and Kemp 2000; Van de Poel 2003; Geels and Schot 2007). In general, these processes are differentiated based on whether factors on the landscape level, the regime level, or the niche level or a combination of them drive the transition process. De Haan (2010) for example distinguishes in this respect between landscape tensions, regime stress, and niche pressures that may lead to transition patterns of empowerment, reconstellation, and adaptation respectively. Basically, the idea is that tensions between landscape developments and the existing regime may lead to the empowerment of a new regime, that regime internal stress between its actors and factors may lead to regime reconstellation, and that new niche developments may pressure the existing regime to adapt to these new changes. Combinations of these patterns or 'a concatenation of patterns' in turn shape the overall transition path or overall transition process. As such, it is easy to imagine at least seven different transition processes: three paths driven by pressures from only one level, three paths driven by pressures from a mix of two levels, and one path driven by pressures from all levels. In addition, one can also enhance this distinction by adding regime actors that may promote or obstruct certain ongoing changes as the result of pressures.

Considering that this research is interested in how the development of renewable energy technologies may affect existing and future energy infrastructures during a transition, and not in studying transitions and how to effectuate them as such, we may focus on one specific aspect of socio-technical transitions: how niches develop into regimes, the effect this may have on the existing regime, both technically and organizationally, and how developments at the landscape level may affect this process. This particular process is well caught by two general transition paths that Elzen et al. (2006) distinguish (referring to Geels 2002); one of substitution and one of transformation. Both paths are depicted by the s-shaped curve in Figure 3.4 and encompass four phases: the pre-development, the take-off, the acceleration, and the stabilization phase (Loorbach et al. 2008, 296).[66]

In the technological substitution path, "the existing socio-technical system is relatively stable, until the new technology breaks through in mainstream markets" (Elzen et al. 2002, 15). One has to consider that while radical novelties are developed in niches outside the existing socio-technical regime, the regime may still be in a phase of incremental change. Because of the technology push character of such a breakthrough, the novelty can stay hidden from the regime for a quite a while. However, when a new technology is able to gain "sufficient internal momentum, and landscape developments put pressure on the existing regime, a breakthrough can occur" (Elzen et al. 2002, 15). As regime actors are caught by surprise, a new socio-technical regime is formed in a phase of radical change. This process is depicted in Figure 3.4 where the third phase represents the shift from the current to the new socio-technical regime and the whole regime is in a state of flux.

In a "technological transformation route, the regime becomes unstable sooner. […] It is heating up, opening up, because of persistent problems or landscape changes" (Elzen et al. 2002, 16). The influence of landscape trends on the regime is

[66] In the pre-development phase, the regime is stable, although there is increasing bottom-up innovation in niches and the landscape is slowly changing. In the take-off phase, change gets underway and forces a rethinking of the state of the system and the regime begins to shift. In the acceleration phase, structural changes take place as the result of the accumulation of social, technical, economic, institutional changes. In the stabilization phase, the speed decreases as a new regime is established. Other research (Perez 2001; Nelson 1994; Loorbach et al. 2008; and Abernathy and Utterback 1978) defines them as the R&D or invention and innovation phase, the early-market or imitation phase, the mass-market or competition phase, and the saturation or standardization phase. The amount of stages differs from 3 to 8 depending on the approach taken. Grübler and Nakicenovic (1991) for example distinguish between 6 stages, Sawhney 2003 distinguishes 8 stages in his infrastructure development model, while Utterback (1994) distinguishes only 3 stages. Please note, however, that most of these accounts focus on individual technologies without reference to technical systems or regimes. Yet Perez (2001, 114) states in this regard that "technological systems evolve along similar lines to those of individual products […] New products [just] represent incremental improvements in the system." Grübler and Nakicenovic (1991) also arrive at a similar conclusion though they also warn that the diffusion of infrastructures follows a different pattern and often precedes the diffusion of the technology.

depicted in the second phase of Figure 3.4. "The loosening up of the existing regime may create multiple windows of opportunity for novelties and stimulate actors to experiment with many technical options" (Elzen et al. 2002, 16). New technologies and niches are thus actively pursued and legitimated by regime problems and landscape dynamics. This manifests itself as a prolonged period of experimentation involving many novelties. Hopefully it leads to a period of 'cooling down', wherein the number of technical options is narrowed and one technology emerges as the dominant one, subsequently making the formation of a new socio-technical regime around it possible.

3.2.2 Patterns in the Technical Development of Infrastructures and Networks

Infrastructures "constantly undergo change, even though they conjure up images of stability and performance" (Ewertsson and Ingelstam 2004, 293). While history shows that they mostly develop gradually over long periods of time, they occasionally may change drastically in the face of urgent malfunctioning. In addition, older systems are continuously being replaced by newer ones (Joerges 1988; Summerton 1994; Ewertsson and Ingelstam 2004; Perez 2002). A convenient starting point for an account of infrastructure development is the work of Thomas Hughes and the Large Technical Systems school that followed. In his book 'Networks of Power' Hughes analyzes the early development of the electricity industry in the US and Western Europe and provides "a compelling account of the way in which technical systems (as opposed to isolated technologies) are brought into being, stabilized, and extended over time" (Jackson et al. 2007, 3).[67]

The account starts by pointing to the key role 'system builders' play. These individuals, groups, or firms (or in some cases institutions), possess both the innovative capacity necessary for producing ground-breaking inventions and the skills for imagining, realizing, and sustaining the techniques, practices, institutions, and other technologies supporting the new invention (Jackson et al. 2007, 3). Thomas Edison is often cited as a prime example.[68] System-building work also goes beyond the technical invention, including organizational, social, cultural, legal, and institutional etc. aspects and requires engineers that can bridge the gap between technologies of the material world and the peoples, organizations, norms and values and expectations of the social world. In addition, this early stage is characterized by a "range of competing designs, small markets, many entrants and high uncertainty in terms of

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[67] Accounts of life cycles and infrastructure development often involve success stories and hence seem to have a bias towards system building. Because the above accounts focus on one technology or infrastructure, they somewhat hide that innovations seldom come alone. In reality, numerous new innovations may emerge that might all be potential successes or new dominant designs. Throughout the life cycle the variety is narrowed down through competition in the market place so that in the end only one or few technologies remain.

[68] While other inventors also had invented light bulbs, or even had a better understanding of the phenomenon of electricity, Edison had the skill and means to envision of a "comprehensive lighting system, including generators, cables, and light bulbs, dedicated above all to the provision of an integrated system of electrical lighting" (Jackson et al. 2007, 3).

technologies, markets and regulations" (Jacobsson and Bergek 2004, 819). It also sees the emergence of the aforementioned niches wherein the new technology is superior to the old in some aspects and where the new technology may be 'nursed' to maturity.

Once a local foothold has been established, "successful systems may undergo complex processes of transfer, adaptation, and growth as they are extended to other places, domains, and communities of use" (Jackson et al. 2007, 3). Two core dynamics are at work here. First, infrastructure development is characterized by inertial qualities, momentum, lock-in, and path dependency. Initial choices matter (Jacobsson and Bergek 2004, 819-824); the choice of a specific core technology and the ties to the actors and markets involved, together with the "cumulative nature of infrastructural development […] means that once set in place or in motion, infrastructures take on distinctive inertial qualities" (Jackson et al. 2007, 4-5). Altering technologies or adjusting to changing actors proves difficult for systems so dependent for their functioning on complementarity and the relationship among their elements (nodes and links). Put differently, infrastructures technologies are locked-in to choices made that in turn may show preference for certain future developments (Murmann and Frenken 2006; Nelson 2008). In addition to this path-dependency, the interaction among system technologies, actors and institutions may also generate a dynamic of its own, creating a certain momentum for future developments. Second, moments of technology transfer are characterized by "the appearance of new challenges and constituencies" (Jackson et al. 2007, 4).[69] Due to their increasing use and growing scale, systems may be forced to facilitate processes which go beyond their initial design. The broader technical, organizational, social, or legal environment also produces reverse salients, i.e. "the particularly intractable challenges, limits, or sticking points on which broad–scale system development grounds and stalls" (Jackson et al. 2007, 4). In addition, changes in technology highlight the "conflicts and incompatibilities with neighboring or alternative systems, and may be the site of particularly intense battles over institutional and commercial standing, community norms and expectations, and the definition and scope of standards" (Jackson et al. 2007, 4). Finally, technology transfer processes are likely to see the rise of new stakeholders in generation, network, and applications, which have their own interests and demands upon the system. Such conflicts of interests are often visible in large technical systems in times of change (Kaijser 1994; Summerton 1994). Because changes in the system (technical or otherwise) represent threats to established system actors, shifts in control and/or balances of power are frequently present. The combination of internal and external dynamics driving the relationship between system elements causes difficult and continuous processes of adaptation and mutual adjustment among system elements and generally lead to subtle changes that adapt the technologies of the old system to new legal, institutional, social, and cultural

[69] "In the development of these complex systems its interconnected and complementary elements need to adapt to the changing needs. Typically not all elements adapt in the same pace. Hence, some of them might lack behind, which has consequences for the entire system" (Jonker 2010, 25-28, following Hughes 1989).

environments, producing variations in 'technological style'[70] (Hughes 1983). It hardly ever implies complete transformations. These processes are also held responsible for the variety of shapes similar infrastructures (electricity, gas, but also water, road etc.) may have in different countries.[71]

These processes of system formation may result in consolidation, an "eventual merger or rapprochement between systems that allows smooth, reliable, and relatively robust interoperation across" (Jackson et al. 2007, 4). This may imply the replacement of one infrastructure by another. Metcalfe and Diliso (following Hughes 1989, 73-75) write in this respect that "when a reverse salient cannot be corrected within the context of an existing system, the problem becomes a radical one, the solution of which may bring a new and competing system" (Metcalfe and Diliso 1996, 78). Mostly, however, "consolidation is achieved through the development of strategic intermediaries, or gateways: technologies, organizational solutions, and/or protocols for interconnection that allow for mobility, conversation, and traffic between otherwise incompatible systems" (Jackson et al. 2007, 4). Examples of gateways are adaptors and converters like plugs that switch from 220 to 110 volts. Once consolidated, infrastructures tend to grow in complexity rather than scope as new consumers and producers claim the use of the network while the broader technical and social characteristics remain roughly the same. Put differently, a dominant infrastructure design has emerged around which further developments are centered, but which do not question the design itself. This also concludes a long process of standardization that began in the previous stages.

The general development of infrastructures leaves its mark on that of networks. In his infrastructure development model (IDM), Sawhney (2003, 26-28) describes how infrastructures develop from their emergence to their maturity in eight stages.

In the first phase, infrastructure technologies start to appear isolated from one another, i.e. as 'technological islands' with no interconnection. These islands are basically demonstration projects that test revolutionary ideas. The commercial potential of these new infrastructure technologies is still uncertain. In the second stage "the new technology is found to be viable and its basic potential is seen in its role as a complement to the old system" (Sawhney 2003, 27). It provides an opportunity to reach those areas inaccessible to the old technology. At this stage, the new technology develops as a feeder and is still a short-haul technology. Afterwards, in stage three, the new feeder technology generates additional traffic for the old system, in effect increasing the old's "catchment area by extending its reach" (Sawhney 2003, 27). At this point the old system is likely to support or encourage the development of the new

70 Roughly defined by Jackson et al. (2007, 4) as "the distinctive look and feel of the 'same' technical system as it appears in differing local and national contexts."

71 Conflict tends to be strong "in cases of more or less catastrophic, and repeated, failure of major components, once this becomes to be perceived as characteristic of the entire system [and] in phases of radical reconstruction, when provisional closure becomes undone. In phases of radical reconfiguration, taken-for-granted support systems and various aspects of the operation of the system – its function, its core technology, its organization, how it is controlled – can suddenly be challenged" (Ewertsson and Ingelstam 2004, 307).

technology as it benefits them. In the next stage, the new technology develops its own long-distance capabilities, creating problems of coordination and standardization in the process. Slowly but surely, the "isolated bits of new technology become directly interconnected and start bypassing the old system" (Sawhney 2003, 27). In the end, the long-distance capability together with the local feeder networks form an own integrated system. At this point the fifth stage is reached in which competition between the old and new technical system starts.[72] Issues such as unfair subsidies, franchise protection (of the old system), and discussions about wasteful competition are likely to hallmark this stage. If the challenge of the new technology is successful, the new technology will be accommodated within the existing order. This, however, is only a prelude to the next stage in which the old system is subordinated to the new because of the latter's higher performance. The "onslaught of new technological developments" eventually pushes the old system into "a subservient role" (Sawhney 2003, 28). In stage seven, the feeder relationship is reversed: "the old system disintegrates into fragments, and only those fragments which can serve a unique niche survive" (Sawhney 2003, 28). They basically fill those gaps or areas that are not attractive for the new system to reach. Instead the remaining fragments may supplement the new infrastructure where they can play a specific or specialized role. As such they function as feeders to the new system. Finally, in the last stage, the new technology or infrastructure dominates until a newer technology appears that restarts the same cycle.

The infrastructure development model shows an interesting pattern regarding the degree of centralization in network configurations. Whereas in the first three to four stages the infrastructure consisted of local networks that served local producers and customers, mainly using the older network for long-distance distribution (if at all), the latter four stages represent an increasing interconnection among the new components, centralizing network operations in the process. In addition, if one considers that the new infrastructure eventually is itself superseded by an even newer one, and the cycle starts anew, the retreat of the infrastructure basically represents a move from a centralized to a decentralized system. As such, a cycle from decentrally to centrally and back to decentrally operated networks can be distinguished.

Three words of caution are in order. First, the IDM was not originally based on energy infrastructures as such, but rather on infrastructures in general and transport and telecommunications in particular. However, it seems to fit neatly with the way in which a transition to sustainability is currently perceived to affect existing energy systems (if one follows contemporary scientific and policy discourse). Second, it looks at the big, or radical, shifts in which an older infrastructure gets superseded by a newer

72 "In all the examples discussed above, we see a consistent pattern. A new technology strikes roots as a feeder to the established system and thereby is seen as extending its reach. The relationship between the new and old technology seems symbiotic and thereby stable and enduring. In effect, the new technology appears to have strengthened the entrenched paradigm. It, however, is eventually shattered with the unanticipated development of an independent system based on the new technology" (Sawhney 2003, 28).

one. It does not look at the finer details of more incremental adaptations that optimize existing infrastructures. Finally, Sawnhey's account of infrastructure development rests heavily on the experiences of so-called 'early adopter' countries of a new energy or infrastructure technology. 'Late starters or latecomers' however, show a different pattern of development; one of planning rather than emergence. Whereas "infrastructure networks in the USA tend to develop in a decentralized, uncoordinated, and bottom-up manner", infrastructure development in France and Canada for example, was often guided by "a blueprint, a grand plan, or a vision of any sort" (Sawhney 2003, 32). When planned, the central transmission network that connects local distribution networks is envisioned from the beginning. Basically, countries that plan skip the first couple of phases and move straight to a centralized infrastructure design. This has both benefits and drawbacks. On the one hand, a bottom-up infrastructure build-up encourages entrepreneurial activity and flexibility to adapt to new developments, but it challenges the forging of a unified system. On the other hand, a planned infrastructure build-up may be specifically designed for certain tasks and as an integrated and efficient system, while it is likely to be rather rigid in adapting to changing circumstances and tasks. In addition to planning, another possibility that deviates from the historical account can be imagined: inverse infrastructures (Egyedi et al. 2009). Inverse infrastructures basically are user-driven, bottom-up, and decentrally organized infrastructures throughout their life spans. The development of the internet is often conceived of in this way, though it remains to be seen whether more central coordination will be required in the future. It may also occur to the 'normal' infrastructures discussed above when path-dependency is strong. Then, pressures towards centralization are negated in favor of keeping the infrastructure decentralized. In this scenario the network is locked-in because of sunk investments in certain 'decentral' technologies and company interests against nationalization. Summing up, Sawhney's infrastructure development model lets us identify at least two alternative build-up processes: first, a planned development of a more centralized system straight from its conception; second, the continuous development along a more decentralized path.

3.2.3 Trends in Infrastructure Organization and Reliability

In contrast to other infrastructures, energy infrastructures are relatively young. While roads, irrigation, and sewers have existed since classical times, energy has only become essential to economies (and human civilization for that matter) in the 19th century, as did many other infrastructures such as railways and the telegraph. It was around 1850 that new energy technologies became technically mature and commercially widespread in urban areas, requiring the development of their own infrastructures for distribution since roads and waterways proved insufficiently capable and expensive (Verbong and Van der Vleuten 2004, 210; Van der Vleuten and Kaijser 2005, 31; De Bruijne 2006, 30-31). "The services and the infrastructures were at first designed to serve small number of users – wealthy individuals and businesses – and were provided on a contractual basis" (De Bruijne 2006, 30). As a consequence of the small scale of energy use and network size, infrastructures were local phenomena driven by local political, economic, socio-cultural and geographical considerations. This led to a wide variety of technologies and governance regimes among them (De Bruijne 2006, 30).

Generally, the small-scale, local energy production and infrastructure enterprises were privately owned and operated (Egyedi et al. 2009, 5). State ownership was rare. However, publicly owned enterprise started to become widespread in the nineteenth century "with the development of public utilities – gas, electricity, water, the railways, the telegraph and, later, the telephone" (Majone 1997, 144). In his historical study of infrastructures between 1840 and 1914, Millward (2004, 1), highlights some of the core drivers of infrastructure governance: local governmental power structures and municipal fiscal considerations (paying for local social expenditures); national economic growth and political unification; ensuring speedy construction; the survival of unprofitable network sections; and the control over network traffic flows. He also noted that the role of governments in the economic organization of energy infrastructures varied greatly across Western European countries (Denmark, France, Germany, Italy, Norway, Spain, Sweden and the United Kingdom) and the US. "Regulation *via* the concession system, municipal ownership, state guarantees of bond interest, profit sharing and nationalisation can all be found" (Millward 2004, 1). A clear divergence in infrastructure governance appeared at the end of the 19th century. Whereas in Europe the "political, economic and military benefits of expansion, standardization and integration of infrastructures ensured that national infrastructure industries became closely interrelated with the rise of nation-states", in the US "most infrastructure industries remained in private hands (Hughes, 1983; Tarr, 1984; Jacobsen and Tarr, 1995; Jacobsen, 2000)" (De Bruijn 2006, 32). Thus in Europe extensive national transportation systems (roads, railways, and waterways) "were either publicly provided or at least heavily controlled or regulated through national governments [often for military and strategic purposes and] were vertically configured and managed hierarchically through large-scale organizations" (De Bruin 2006, 32), while in the US "public bodies – initially municipalities and later state governments – increasingly regulated private infrastructure providers in return for a geographical monopoly (Jacobsen, 2000:76) [, i]nstead of actively engaging in the provision of infrastructures" (De Bruin 2006, 32). Nevertheless, even in the US the limited possibilities for competition in infrastructures were recognized. Despite these developments, before World War I, energy infrastructures such as electricity and gas remained rather decentralized and local in nature, in contrast to national railways and telegraphy networks.

It was also at the end of the 19th century when energy infrastructures encountered the first real concerns regarding reliability. A combination of a steadily increasing user base, the existence by then of many competing energy providers (with their own networks), and energy's rising importance to industry and national economic growth lowered tolerance for power interruptions and failures among the general public, industries, and governments, showing also the vital importance of energy systems to industrialized countries (Dupuy 1992, 53). It became clear to infrastructure service providers that reliable, efficient, and high-quality service necessitated the "continuous or near-continuous operation of infrastructure systems, in order to fulfill public demands" (De Bruijne 2006, 31). This differed from earlier decades where the technical assets (and their divergent architectures) of infrastructures were the cause of differences in reliability performance among infrastructure companies (Jacobsen 2000).

The first half of the 20th century saw a rapid expansion of energy infrastructure industries and the use of energy. New technical possibilities "enabled mass production of infrastructure services and produced economies of scale" (De Bruijne 2006, 32). In addition, for reasons of national economic and social development, "infrastructures had to achieve nationwide coverage and provide universal services at low prices to achieve this goal" (De Bruijne 2006, 34). Consequently, the small-scale and localized infrastructures expanded rapidly and merged to form larger regional and eventually national networks, while their low price diffusion made them available and affordable to an ever-increasing number of users.[73] At the same time, "small private companies merged, were subject to new regulation, or even taken over by governments" (Egyedi et al. 2009, 5). In turn, infrastructures quickly spread beyond their initial design (Verbong and Van der Vleuten 2004). Governments followed a "supply-oriented logic of network deployment" (De Bruijne 2006, 34) in order to keep up with societal implications of infrastructure and energy demand growth (Van der Vleuten 2004).[74] Policy makers opted for national monopolies to achieve these goals; a "single entity controlled all facilities, operations, and administrative functions and was obliged to serve on demand within its territory" (Kessides 2004, 35-36).

The rapid expansion of energy infrastructures was accompanied by increasing public intervention on both the local and national level and a shift in organizational forms towards new levels of control and coordination (Chandler 1977, 1993). On the one hand, "[m]unicipalities stepped in as guardians of the public interest and took over the remaining local private infrastructure companies" (De Bruijne 2006, 33), while national governments had economic and political goals to worry about. For example, infrastructure services and products were considered essential to the military and socio-economic development of countries (Jacobsen and Tarr 1995; Millward 2004). It would not be long before the latter were to gain prominence over local issues. In the end, "[f]orms of central planning and management penetrated nearly all functions related to infrastructure operations, such as planning, design, construction and maintenance" (De Bruijne 2006, 33). As a consequence, local and national governments became involved in the "planning, ownership and management of many of the newly contrived civil infrastructures, such as electricity [and] gas [who] were increasingly considered 'public local goods' which had to be "[f]reely available to all individuals at equal cost within a particular environment" (De Bruijne 2006, 31). This increase in public involvement in energy infrastructures in turn stimulated technical standardization and the expansion of infrastructures in urban areas. On the other hand, bad "public experience with large-scale inefficiencies, poor performance and a

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[73] "In fact, the continuous reliability and low-cost availability of services to large populations was one of the overriding arguments for increased public involvement in the provision of infrastructures" (De Bruijne 2006, 31).

[74] U.S. electricity industries, for example, were scrambling to keep pace with electricity consumption, which rose at an average rate of more than eight percent annually from 1945 to 1965 (Jacobsen 2000, 136).

bewildering variety of privately produced infrastructure services" (De Bruijne 2006, 31) helped to create a "resistance to private ownership, management and competition in infrastructure industries" (Jacobsen 2000, 26). Hence it was believed that larger infrastructures could be more reliably and efficiently managed as public or private monopolies supported by top-down centralized control and a high degree of standardization (Nightingale and Poll 2000; Graham and Marvin 2001). In addition, organizational centralization was accompanied by developments in information technology that created advantages for centralized management and control. IT "enabled fast, reliable management of large information flows and expanded abilities to deal with the increased complexities of operations associated with infrastructure expansion" (De Bruijne 2006, 35). Consequently, the scale and scope of control increased dramatically, making central control the most efficient and reliability of service provision more secure. After World War II, with the emergence and growth of the welfare state and the introduction of information technology, "the ideal of a large-scale, nationalized and integrated infrastructure industry reached its high-water mark" (De Bruijne 2006, 34). The central planning and control approach taken to rebuild war-torn economies carried over to infrastructures. By 1970, nationally integrated infrastructures provided nearly universal services to households of industrialized countries (Verbong and Van der Vleuten 2004, 206), although differences in the level of centralization in ownership and management remained across industries, electricity and telephony for example being more centralized than water and public transport (De Bruijne 2006, 36). Overall, however, the dominant organization in infrastructure utilities was the vertically and horizontally integrated monopoly.

During this period, the reliability of energy infrastructures increased considerably due to the "centralization of infrastructure industries under public ownership and the interconnection and integration of small-scale and technologically diverse infrastructure systems under central control" (De Bruijne 2006, 33). Basically, control systems co-evolved with technical (complexity and capacity utilization) and economic expansion (Nightingale et al. 2002, 9) in two ways. First, "the new large-scale, vertically integrated hierarchical organizational structures" (De Bruijne 2006, 33) created a setting in which engineers and managers could (and were allowed to) centralize control which in turn increased levels of reliability and efficiency. Second, new information technologies allowed for the development of sophisticated control equipment (Chandler 1977; Beniger 1986; Nightingale and Poll 2000), which in turn "enabled operators to [remotely] manage and optimize load and traffic flows in the still expanding infrastructures" (De Bruijne 2006, 34). Though information technology had always been important for system control, the reliable operation of large-scale infrastructures required ever more information processing, resulting in the formation of control rooms, i.e. "centralized locations from where (portions of) infrastructures could be monitored and managed" (De Bruijne 2006, 34). Automation further helped in the coordination of the activities taking place in these control rooms. In the end, a single organization controlled "every aspect of a utility – facilities, operations and administration – and determined which services to provide to essentially captive customers" (Kessides 2004, 1). In addition, reliability "became a key characteristic of the service provided in vertically integrated and state-owned or regulated infrastructures" (De Bruijne 2006, 33-34) and the prevention of "potentially devastating events, e.g. large-scale cascading failures, a policy goal. Key to ensuring uniform levels of reliability and universal service provision (on a now national scale) was the uniform design of infrastructure components. Centralized planning and construction helped in this respect.

The end of the 1970s also saw the end of the dominant trend in infrastructure development of technical growth and expansion and organizational centralization and vertical integration (Abbate 1999; Coutard 1999). Three main causes for this can be identified. First, the economic benefits of economies of scale and scope seemed all but saturated under existing paradigm of centralization. Technologies were mature and geared towards continuous and large-scale provision. Infrastructure designers started to realize the adverse effects of too much centralization: economic inefficiency, lack of innovation, and lack of flexibility to deal with rapidly changing environments (De Bruijne 2006, 37). Please note that a lack of reliability was not among them. Second, the development of new information and communication technologies allowed for fundamentally rethinking and redesigning infrastructures both technically and organizationally. Whereas information technologies had initially helped to develop centralized control until the 1960s, by enabling "vertically integrated command and control over large-scale infrastructures and [changing] the perceptions of the capabilities of large-scale systems" (De Bruijne 2006, 37), now it started to undermine this logic. Personal computers "allowed infrastructure industries to scale down technologies, to decentralize and to disintegrate management and create new functions and capacities [promising] significant benefits in speed and volume of service provision in infrastructures" (De Bruijne 2006, 37). Third, the rise of the idea and practice of network-based economic organization in postmodern economies, i.e. the move from mass-production and industry to a knowledge-based society and individual consumer oriented products, did not suit the large-scale vertically integrated organizational structures. They were deemed "incapable of dealing with the increasing pace of technological changes, volatility in supply and demand, shorter product life cycles and global, hypercompetitive markets in this dynamic environment [because these] require flexible and decentralized forms of organizing" (De Bruijne 2006, 39-40).

Combined, these economic, technical, and organizational developments reshaped infrastructure operation and organization and paved the way for privatization, liberalization, unbundling, and deregulation of these infrastructures. This institutional reform signaled the end of "[t]he era of integrated monopolies, operating infrastructures and providing the totality of services" (De Bruijne 2006, 45). Instead, network industries would be unbundled both horizontally and vertically, with different owners for potentially competitive components and natural monopoly components. Infrastructures would also no longer be "[o]rganizationally unified or integrated, even though they may technologically be based around… a single technology" (De Bruijne 2006, 11). In other words, the centralized infrastructural organization structures were to be replaced by horizontal, network-based structures "that had to exchange and process increasing amounts of information to coordinate their actions" among its multiple cores (De Bruijne 2006, 40).[75] Consequently, both the amount of actors and technologies in infrastructures increased rapidly.

This also impacted reliability. The new decentralized, non-hierarchical industry structure is "[d]elayered, highly flexible, and controlled by market mechanisms rather than administrative procedures" (Miles and Snow 1995, 5). Whereas interaction between entities in vertically integrated structures was top-down, cooperative, and/or largely restricted, in the new approach coordination and communication problems between the different entities may arise as "[a]ctors and organizations have conflicting interests, values and strategies" (De Bruijne 2006, 46). However, hope lies in the same IT technologies that helped bring this change of organization about: markets may be facilitated by intelligent distributed technologies and new modes of infrastructure organization (De Bruijne 2006, 46).

3.2.4 Transferring Past Experiences into Future Expectations

The accounts of transition processes and the technical and organizational dimensions of infrastructure development allow us to distill general patterns that may guide our thinking about a transition to sustainable energy systems, or at least provide us with some expectations. The purpose is very modest, however: "while historical and comparative studies of infrastructure are unlikely to deliver anything as neat as a blueprint for action, they *can* – and indeed *should* – shape and guide thinking about present efforts at infrastructure development, in the sciences as elsewhere. This at least is what we have sought to wrest from historical and comparative study: not rules, but heuristics; not a map, but principles of navigation" (Jackson et al. 2007, 2). As such, assuming the ongoing relevance of history despite new and potentially revolutionary technologies, we point to some general observations.

Looking back at the transition process and multi-level perspective of transition theory, we can differentiate between four general transitional phases in the development of a niche into a regime or from one regime to the next. The first phase concerned the invention and introduction of new technologies. The second phase was regarded as the consolidation of the new niche regime. The third phase was special: it marked the shift from niche to mass market technology that may bring its own requirements for operations. The fourth phase concerned the consolidation of the new dominant regime. The various levels also pointed out a few noteworthy matters. New technologies can be distinguished at the hand of their radical or incremental nature, placing them in the niche or regime respectively. Regime changes could also be differentiated in terms of their gradual or more abrupt nature and their landscape, regime internal, or niche related drivers. Finally, the landscape level highlighted the

[75] Basically it meant a transition from vertically integrated monopolies, large-scale technologies (economies of scale), central control, ownership concentration / few actors, public ownership, tight coupling of core functions, and regulated prices to an unbundled competitive system, small-scale (intelligent) technologies, decentralized and run by markets, dispersed ownership / many actors, public-private or private ownership, disaggregation of core system functions, and market prices (De Bruijne 2006, 45).

relevance of the broader environment in which regime or infrastructure change takes place and that might produce important enabling and obstructing factors.

Next, the insights from the LTS and IDM showed us how energy infrastructures generally grew from local, small-scale, and simple infrastructures to national, large-scale, and complex systems following a certain pattern, but where technical possibilities and the social environment shaped concrete characteristics and developments in their own right. In addition, they showed how new networks begin as feeders to an existing infrastructure, then necessitate their own transmission network for operations, signaling the beginning of a need to coordinate the efforts of all individual or local feeders, only to finally revert back to the function of a feeder once a newer infrastructure arrives. There was a clear movement from more decentralized to gradually more centralized systems that eventually reverted back to a more decentralized structure when it was itself superseded by a new infrastructure. Of course, some notable exceptions were also highlighted.

Finally, the historical account of infrastructure governance and reliability showed a movement from decentralized organization and private ownership and operation before WWI to centralized and hierarchical forms of organization and public control until the 1970s to a network based organizational structure with a regulatory state (the network being public and production and sales private) since then. However, it also noted that these changes were largely due to political and socio-economic concerns and developments in information technology, rather than changing energy technologies or increasing size and complexity of networks and growing numbers of consumers. Politics, economics, military, and socio-cultural concerns largely shaped infrastructure development (Millward 2004, abstract). Finally, it was noted that the concept of reliability changed over time as per changing infrastructures and political concerns, and that the control requirements and possibilities did not necessarily co-evolve smoothly.

Bringing all aspects together, an overview can be made (see Table 3.1). Though the overview is rather simplistic and phenomenological (no causality is implied, though investigation seems warranted) it nonetheless seems to point to a very general co-development of the technical system configuration and organizational structure of energy infrastructures. This should not be too surprising since the aspects are supposedly heavily related in socio-technical systems, hence the development of the concept in the first place. It is important to note, however, that the overview gives no assurances as to whether events in the energy transition will occur in the same pattern.

Table 3.1 General patterns in infrastructure development and energy transitions

	Phase 1 1850-1914	Phase 2 1914-1945	Phase 3 1945-1975	Phase 4 1975-2010
Technology / operation	Local, small-scale, decentralized	Regional / national scale, rapid expansion, increasingly centralized	National coverage, large-scale, central control and operation	National / International, large-scale, central operational control with increasing decentralization
Governance / organization	Private ownership, vertically separated	Public-private interference, Increasing vertical integration	Public ownership and operation, vertically integrated monopolies	Mix of public and private ownership and operation, unbundling of competitive and network parts

3.3 Conclusion

This chapter presented the practical challenge an energy transition represents to maintaining reliability and looked into theories on socio-technical transitions and historical accounts of energy infrastructure development, both technical and organizational, to derive some rough expectations regarding the transition to sustainability. In the end, the transition from fossil fuels to renewables involves a series and variety of technical changes with unknown organizational consequences. Only some broader infrastructure development patterns moving from local and decentralized networks and organizational structures to national and centralized ones before becoming more decentralized again were discerned. This is a somewhat unsatisfactory answer as it sheds more light on the process than on the relationship between technologies and organizational structures and hence does not allow for specific expectations. Nevertheless, discussing the energy transition provided some important background information and stressed the perspective taken in this research - that of aligning organizational structures to technical changes. The central question in this respect remained unanswered: what may the technical changes stemming from the introduction of renewable energy sources and carriers imply for the organization of energy infrastructures in light of reliability; and how to assess this? Chapter 4 will now address this.

Part II

4. A Framework for Alignment

With the conceptual groundwork laid and the practical challenge elaborated, we are ready to develop a framework that allows us to approximate what organizational structures complement particular technical characteristics of future renewable energy infrastructures in light of reliability. In section 4.1 four steps are proposed that together constitute such a framework for alignment. First, identifying those aspects of technical system operation that involve coordination among entities (technical functions); second, allocating which entities are responsible for those functions (and to what degree); third, inquiring how those entities should coordinate for control per technical function; and fourth, combining the results of steps two and three to identify the overall required organizational structure. The core challenge in this endeavor is translating specific sets of technologies into their coordination requirements. A possible solution lies in the use of the concept of coherence as a design principle. Its premise is to relate transactional characteristics to specific technical functions of infrastructures and in this way bridge the technology-organization divide. If successful, it moves beyond the mere comparative link found in the literature on socio-technical systems and infrastructure history as it provides a mechanism to relate the technical operation to its coordination requirements. Afterwards, section 4.2 will briefly summarize and point to some immediately apparent possibilities and limitations of the framework.

4.1 Bridging the Techno-Organizational Divide

This section tackles the core challenge in this research; how to express technological characteristics in terms of their organizational requirements? Where to start searching for answers? Looking at the insights presented in the previous two chapters a number of considerations appear important.

First, regarding technology, we are interested in finding those aspects of technical operation that affect system complementarity and involve entity coordination. While new renewable energy and infrastructure technologies may alter technical components, as long as they don't alter the responsibilities of and relationships between entities, there need not be any change in organizational requirements, and hence in the organizational structure. One may, for example, replace one pipeline with a newer model without changing anything in terms of operation. In other words, we are not interested in technical assets like pipelines and wires as such, but in those aspects of technical functioning that ensure the complementarity of infrastructure technologies across the supply chain. Hence we should focus on the operational process and procedures and the technologies utilized therein, rather than mere technologies. At the same time, we should not forget that some aspects of technical functioning might be more relevant to reliability than others. As Moteff et al. wrote (2003, 11), we need to "identify which elements of the infrastructure are critical to its function[ing]." Not all assets or operations are equally critical to sustain operations.[76] So, what aspects of technical operation are critical to safeguarding system complementarity?

Second, even with such aspects identified, the question remains how to establish which organizational requirements may follow from them and how to measure this? Here, the two key dimensions of organizational structures identified earlier shed some light on how to proceed; the entities involved in technical operation (the who does what, when, and how) and the nature of their interaction (hierarchical / horizontal). Regarding the former, the question needs to be posed which entities are involved in the operation of an aspect and what is their responsibility in this regard? It is very likely, for example, that decentral solar pv power will shift involvement from electricity producers and transmission operators to 'household prosumers' and distribution operators with regard to electricity production and transportation respectively. Concerning the latter, we need to find a mechanism that relates infrastructure operations to the coordination requirements they involve among entities in order to bridge the technology-organization divide. A possibility lies with the concept of control mechanisms that facilitate the reliable functioning of technologies. Yet when do control mechanisms require close monitoring and central coordination? And what about other infrastructure features that may affect coordination requirements?

Finally, how may we combine the outcomes of these two dimensions into one organizational structure per aspect and how may we combine these outcomes for each aspect into one working whole? Many aspects of operation may need to be addressed. How to deal with the possibly complex and varying results?

In the end, the contours of a framework for alignment based on four steps from technical characteristics of energy infrastructures to organizational structures start to emerge.

4.1.1 Technical Functions and Control Mechanisms

This step addresses the question what aspects of technical operation are critical to safeguarding system complementarity and involve entity coordination? A convenient starting point is given by the literature on coherence by Finger, Künneke, Groenewegen, and Ménard.

In their 2008 article, Künneke et al. start off by defining the concept of technical criticality in infrastructures as "those aspects of the technical operation and management of any given infrastructure that are critical in order to meet expectations with respect to the technical functioning of these systems" (Künneke et al. 2008, 4). This entails first specifying the expectations with respect to the technical functioning of infrastructures. Doing so, they define reliability, safety, and security of supply, where the focus then turns to reliability only. They define reliability as "the ability of

[76] Moteff et al. (2003, 11) also noted however that "the size and complexity of […] infrastructures can make identifying which assets of an infrastructure are critical a daunting task", pointing out that the US electricity infrastructure "includes 92,000 electric generating units (including fossil fueled, nuclear, and hydroelectric units), 300,000 miles of transmission lines, and 150 control centers, regulating the flow of electricity."

[a] system to 'perform / maintain its functions in routine and also in different hostile or/and unexpected circumstances" (Künneke and Finger 2007, 309). Then one needs to find ways how to identify those aspects of the technical operation and management of infrastructures that can be considered critical in regard to the expectation of reliability. Special attention goes to the defining characteristic of infrastructures: strong technical system complementarities.[77] Here two aspects are discerned that determine the criticality in infrastructures: a) critical assets and b) "specific functions that are essential to safeguard the technical performance of infrastructures" (Künneke et al. 2008, 5). The former are assets that are fundamental to the functioning of a technical system. They include the more tangible objects such as traffic control systems in railroads, transmission lines in electricity, or pumping systems in the water sector. Künneke et al. focus, however, more on the second notion, the technical functions of criticality. While the functioning of assets is a purely technical issue, remaining limited to one chain component, technical functions focus on how varying assets work together and hence may involve coordination among supply chain entities. They distinguish between four technical functions that can be considered critical for safeguarding the technical complementarity and functioning of networks: interoperability, interconnection, capacity management and system management (Finger et al. 2006, 11-12).

Interoperability focuses on the "mutual interactions between network elements" and as such "defines technical and institutional conditions under which infrastructure networks can be utilized" (Finger et al. 2006, 11-12). The main concerns are the complementarity between energy sources or carriers and delivery systems, between energy quality/characteristics and application requirements, and regulatory conditions for network access. Issues raised include the complementarity between the natural gas produced and pipelines specifics, or the harmonization of the purity of natural gas with the specifications of domestic applications (heating, cooking equipment). There is also a relevant strategic aspect related. Interoperability "determines the conditions of use as well as the rules for entry and exit to [a] specific facility" (Künneke and Finger 2007, 312). Moreover, different types of natural gas qualities and pipelines in different countries may hinder cross-border energy flows, as they require upgrading or downgrading natural gas or a transfer facility. Ultimately, these issues require technical norms and standards in order to ensure complementarity. This makes the creation of such codes and standards just as important as upholding them for reliable functioning of the system. In addition, the integration of possible future components also requires some careful preparation or planning in terms of standardization.

[77] This focuses a discussion of infrastructure reliability on the network. That is not to say that generation and application are not relevant, but it is to say that it is helpful for a discussion on reliable technical functioning to focus on the network discussing generation and application in relation to the network. As such, production sites and consumers are treated as network entry and exit points respectively. Referring to 'infrastructure technologies', then, still includes all technical artefacts involved in the various infrastructure components that are required to operate an infrastructure.

Interconnection deals with the "physical linkages of different networks that perform similar or complementary tasks. As such, interconnection is closely related to the technical system boundaries" (Finger et al. 2006, 11-12). Local gas distribution pipelines or electricity grids often exist as parts of a wider national and continental transmission networks. There is also a similar difference in oil distribution between oil tankers and pipelines and various national truck-based delivery systems. Moreover, next to facilitating these linkages between networks, new entry and exit points in the form of producers and consumers need to be connected and disconnected continuously. Another important issue is transmission planning, i.e. the design of "system additions to maintain reliability and to minimize cost" (Künneke and Finger 2007, 311). Networks are often very dynamic, despite their static appearance. New connections are regularly added when distribution networks are extended to include new customers or when transmission capacity is increased to allow for additional energy flows. Such network allocation matters need to be addressed carefully. Generally, increasing interconnection has a positive effect on system reliability because one system may provide additional resources or capacity to another in times of distress. For example, an unexpected outage at a power plant in a local stand-alone system may lack sufficient back-up capacity. However, interconnection may also pose a challenge to reliability of the overall system when failures in one part of it start to cascade to another.

Capacity management concerns the allocation of "scarce network capacity to certain users or appliances" (Finger et al. 2006, 11-12). Questions about the scope and capacity of the network, access rights, the facilitation of actual access, and the daily operational management of the technical flows through the network are addressed. Issues pertain to the operational balancing, tactical management, and strategic management. Operational balancing is concerned with the continuous technical balancing of a system, i.e. the regulation of energy flows (voltage or pressure) and checking the energy content (quality), automatic protection to minimize "damage to equipment and service interruptions caused by faults and equipment failures" (Künneke and Finger 2007, 311), and real-time disturbance response. Put differently, typical concerns are lowering intermittency, i.e. the degree to which the system lacks constant levels of productivity, congestion management, and preventing and responding to equipment outages in order to continue operations (McCarthy et al. 2155-2158). The former two necessitate control centers to monitor and regulate energy flows from a distance and instantaneously. The latter benefits from the development of routines that assist in adjusting generation and transmission (equipment) to restore a system to the scheduled balance as quickly and safely as possible. Redundant assets may prove very valuable for both. Tactical capacity management relates to the "allocation of existing resources in order to meet the expected demand" (Künneke and Finger 2007, 309). This implies first of all unit commitment and capacity utilization, i.e. "deciding when to start up and shut down generating units" (respecting start-up and down rates and their impact on generation efficiencies) and which parts of the network to use for transportation (Künneke and

Finger 2007, 311).[78] This also implies managing the expected loss of load (in hours or days) in terms of frequency and duration (McCarthy et al. 2153). Secondly, it concerns maintenance scheduling, i.e. when and where to perform periodical checks and execute repairs of production facilities and networks while not jeopardizing the reliability of service provision (Künneke and Finger 2007, 310). Strategic capacity management addresses the long-term planning of production facilities and energy sources or fuels in order to have sufficient generating capabilities available to meet future requirements. It relates to the ability to expand or diminish facilities easily and cost-effectively (McCarthy et al. 2157). For example, the choice of generation technologies, such as the building of new coal based power plants or the use of carbon capture and storage, and preparations for the incorporation of new renewable energy sources in daily infrastructure operation fall under strategic capacity management.

Finally, system management "pertains to the question of how the overall system (e.g. the flow between the various nodes and links) is being managed and how the quality of service is safeguarded" (Finger et al. 2006, 11-12). This mostly comes down to the continuous aligning of supply with demand, both in quantity (over and under production and consumption) and quality. What is the extent to which an energy system is able to "adapt to changes in the quantity [and type] of energy demanded or location of demand" (McCarthy et al. 2007, 2157)? What is the degree to which a system can adapt to changing conditions? There needs to be a buffer or margin between installed generation and transport capacity on the one hand and expected demand on the other. Important issues thus include security of supply and storage possibilities in order for the system to remain flexible when faced with demand fluctuations. System management hence differs from capacity management in that it focuses on the entire infrastructure rather than the network. Concerning quality, an eye needs to be kept on the trade-off between affordability, availability[79], reliability, acceptability, and increasingly sustainability. What are consumer preferences in this regard and how flexible is the system in meeting them? Or, more attuned to this research, how can changing preferences towards greener energy sources be met without compromising reliability?

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[78] Regarding unit commitment, commonly energy suppliers need to ensure sufficient production capacity to satisfy demand and contract transport capacity. The system operator then checks whether the system is physically able to deliver the intended amount and calculates whether the committed capacity is sufficient to meet expected demand (Künneke and Finger 2007, 309-310).

[79] Regulatory efforts to ensure universal service provision also fall under this heading. Here we differ from Künneke and Finger who have put such an issue under the heading of interconnection. Of course, the actual connecting of factories, households, and retail stations is a matter of interconnection.

Table 4.1 Critical technical functions and their main concerns

Interoperability	Interconnection	Capacity Management	System Management
- Facilitating component complementarity - Planning for future components	- Facilitating existing linkages - Transmission planning	*Operational balancing* - Regulation energy flow and content - Automatic protection - Disturbance response *Tactical capacity management* - Unit commitment - Maintenance scheduling *Strategic capacity management* - Generation planning - Fuel planning	- Manage system flow - Quality of service

To facilitate the proper operation of the four critical technical functions certain control mechanisms are required to monitor and correct important reliability parameters.[80] For example, interoperability requires the setting of norms and standards and the enforcement of them once developed. Alternatively, technical complementarity may come from voluntary adherence to existing standards. Interconnection requires an office to monitor and facilitate interconnection points and a planning office to incorporate future network links and entry and exit points. Capacity management requires remote control over energy flows. This involves a control center, established routines, regular checks, redundancy, back-ups, emergency procedures, support teams, a capacity or slot scheduling (front) office, a contract execution (back) office, and an office dealing with network planning. System management finally benefits from stable energy markets, storage possibilities for strategic reserves, and market monitoring to anticipate changes in supply and demand. The control mechanisms needed to operate a technical function of a future renewable energy infrastructure should be clarified during the discussion of that technical function and follow logically from it during the application of this step. Comparisons to similarly operated contemporary energy systems also help in this regard.

[80] Please remember that "control is required when a match between actual and intended performance cannot be reliably maintained, typically because requirements change or cannot be designed-in. In these instances control systems monitor, compare and modify the inputs and parameters of various subcomponents in a co-ordinated way to ensure that the overall system behaves as intended" Nightingale et al. (2003, 484).

4.1.2 Allocating Technical Functions to Infrastructure Entities

The technical functions are set at the level of the infrastructure. As such, it is unclear which particular entities are involved in facilitating them. If we wish to identify the organizational requirements of a technical function, however, we need to be able to translate the technical functions into concrete responsibilities for specific supply chain components. In other words, which entities are responsible for the facilitation of a certain technical function and to what degree?

Regarding who might be responsible, chapter 2 showed that infrastructure supply chains are made out of several components, i.e. sources, production, trade, transmission, storage, distribution, metering, retail, consumption, and regulation, that represented technically separable entities. While the description of the various entities in chapter 2 already shed some light on which entity is responsible for what tasks to ensure reliable functioning (for example, operational balancing is the responsibility of an operator while interoperability may be the responsibility of all entities), sources and consumers are less obvious. We urge for their inclusion, however, since we have already seen that consumers can take on the role of producers in distributed energy systems and that failures in the networks of energy sources may create problems for the production of energy carriers such as electricity and hydrogen. Of course, such generalizations of entity responsibilities are based on the observation of the operation of existing energy infrastructures. This research, in contrast, cannot make such observations with regard to future energy systems. The challenge in this regard is how we can know who is *likely* to be doing what, when, and how. The question posed is: which of the supply chain entities so far defined are likely to be required for or involved in facilitating a certain technical function? Put differently, if operational balancing or the upholding of standards is involved, who is likely to take care of it? In order to allocate the technical functions for future renewable energy systems a thorough analysis of the technologies expected to be present in a future system needs to be undertaken and interpreted in light of the entities described in chapter 2. In addition, we suggest learning from comparison with similar present-day infrastructures that seem to operate reliably. Hydrogen gas pipelines or liquefied hydrogen truck distribution might be very similar to that of natural gas or oil delivery today and might therefore be a guide as to what one might expect to be a reasonable division of tasks. While hydrogen and natural gas pipelines may have different material requirements, they are likely to be operated very similarly from a organizational point of view. In contrast, distributed electricity generation might be rather different from a system of coal- or gas-fired power plants. Chapter 5, where we study the electricity, natural gas, and petrol sectors in the Netherlands to explore the framework for alignment, gives us the reference material we need for similar systems. Of course, this leaves unanswered the question of what to do with the future energy systems that are radically different from the ones today. In that case, only a thorough study of the expected technologies in the vision of a future renewable energy system remains. While this seems rather abstract and difficult to do, but if technologies of a future system are well-described, we should be able to identify the entities responsible for their functioning.

In addition to identifying who is involved in facilitating a technical function, we must realize that not every entity is equally involved in interoperability, interconnectivity, capacity management, and system management. This leads to a second distinction besides involvement or not. Entities may be responsible for key operational tasks (strong direct involvement), be responsible for executing their part in daily operations (weak direct involvement), or play a more supportive role. For example, while TSOs operate pipelines, producers and retailers are directly related to pipeline operations, and retailers and meterers provide the necessary data but do not operate the network as such. Entities may also be the main responsible in the operation of a function, while others carry out tasks in accordance with them. For example, TSOs may play a leading role in operational balancing with DSOs acting in accordance to them. Alternatively, DSOs might also have a more independent character with the TSOs functioning more as a sort of connectors of regional networks. Finally, some entities might only influence technical operation indirectly. While traders for example may not actively contribute to system management as such, their actions may nevertheless impact it. Another example is regulators, whose codes and standards and operating procedures set the conditions under which the system operates, but who are not actively involved in the daily technical operation itself. This urges for their inclusion as responsible entities even though they are not part of the supply chain per se. Of course, a distinction must be made here between those regulations that target economic and social performance criteria from those that relate to technical reliability. This allows for six general classifications regarding the degree of involvement in facilitating a technical function: no involvement, indirect involvement, supportive involvement, weak direct involvement, strong direct involvement, and leading involvement. Once all critical technical functions have been mapped this way, an overall picture emerges that provides some insights as to which entities are key and which are relevant to a lesser extent.

A final issue is determining the number of a particular involved entity. How many producers or retailers are there? How many TSOs and DSOs are involved in operating a network? Merely stating, for example, that retailers are directly involved in facilitating interoperability does not convey how many retailers are involved. Yet this matters greatly in determining the complexity of the organization. Supplying a few thousand fuel stations is not the same as supplying millions of households. Having a single producer of natural gas compared to many electric power companies or a single TSO (as in the Netherlands) compared to a few TSOs (as in Germany and the US), for example, has implications for network operations. Of course, it is difficult to count the specific amount of representatives of a particular entity involved in future renewable energy systems. Nevertheless, it should be possible to estimate whether a single, few, or many representatives of a particular entity are involved. By doing so, an image is created that shows which entities are involved, to what degree they are involved, and how many representatives of each particular entity there are. This result can be capture in one overview:

Table 4.2 Allocation example: electricity system entities and their responsibilities

Entities	Amount	Inter-operability	Inter-connection	Capacity Management	System Management
Sources	Few	--	--	--	-/+
Production	Few	+/-	--	+	+
Trade	Many	--	--	-/+	-/+
Transmission	One	+	++	++	+
Storage	Irrelevant	--	--	--	--
Distribution	Few	+	+	+	+
Metering	Many	--	--	-/+	-/+
Retail	Many	--	--	+/-	+/-
Consumption	Millions	--	--	--	-
Regulation	One	-/+ or +	--	-/+	-/+

Legend: 6 degrees of involvement are distinguished from least to most:

-- No involvement.
- Indirect involvement (entity affects operation or planning).
-/+ Supportive involvement (set ramifications, data providers, oversight).
+/- Weak direct involvement in daily operations (entities involved in operations).
+ Strong direct involvement (key operational responsibilities).
++ Leading involvement (central coordinating entity, system operator).

4.1.3 Establishing Coordination Requirements of Technical Functions

Next to identifying the involvement of entities in the operation of technical functions, we need to establish the coordination requirements among them.[81] How do entities need to interact to coordinate for control? Literature so far hints at two possible inroads to addressing this question. First, we may focus on the control mechanisms employed in operational procedures and use the concept of coherence as a design principle to relate them to the transactional characteristics they embody and the coordination requirements that follow from them. When do they require central coordination or not? Second, the literature on reliability failures in large technical systems revealed certain features of infrastructures that affect the operation of control mechanisms. These need to be taken into account as additional considerations. Let us now look at both in turn.

[81] It is important to reiterate here the exact difference between coordination and organizational requirements to avoid confusion. While both look very similar at first glance, coordination refers to the nature of interaction among entities in terms of a more hierarchical, top-down fashion (often from a central control center) on the one hand and a more horizontal, bottom-up fashion (where autonomous entities interact) on the other. Organization in turn adds the aspect of how many entities are involved and the degree of their involvement (step 2) in order to merge both aspects into categories of vertical integration. Central coordination between one or two entities might look very different from central coordination among many entities for example.

4.1.3.1 Critical Transactions and Modes of Organization

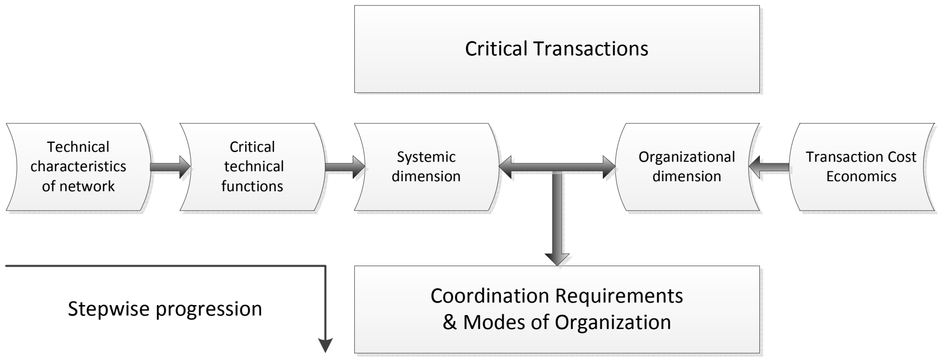
It was noted earlier that Finger, Künneke and Groenewegen (2005 - 2008) hypothesized that the economic, social and technical performance of infrastructures is dependent on the "degree of coherence between the technical and the institutional coordination" (Finger et al. 2006, 13). If so, the concept of coherence can also be used as a design principle. If high degrees of coherence between the coordination mechanisms and scope of control of the technical operation and the institutional organization roughly imply improved overall performance (though they may lead to less incentive for innovation (Jonker 2010)), one can argue that centrally operated technical systems require more hierarchical organizational structures while more distributed systems can be facilitated by autonomous entities. If we focus on reliability only, forsaking any performance trade-offs, we then have an opportunity to optimally design the structure of the organizational dimension according to the technical dimension's requirements. Following this reasoning, Künneke et al. set out to develop a framework for aligning institutions to technologies in their 2008 article[82].

They present a step-wise progression from the technologies of infrastructures (in our case the critical technical functions) to their coordination requirements and the so-called 'modes of organization'[83] that should enable their adequate facilitation. They do so in three basic steps (see also Figure 4.1). First, they identify the control mechanisms necessary for the operation of infrastructure technologies and categorize them in terms of the scope of control involved (system, subsystem, or component) and the speed of adjustment that is necessary, i.e. how quickly is action required for the operation of the control mechanisms (immediate term, short term, medium term, or long term). Second, they classify these categories of control in terms of their transactional characteristics with the help of literature on transaction cost economics. Although these transactional characteristics are intended to be related to more or less hierarchical forms of economic organization, they are here adapted to enable distinguishing more or less centralized operational requirements. Therefore, by identifying the transactions involved in facilitating control mechanisms, they are able to establish the coordination requirements of them. Finally, Künneke et al. translate the sum of the resulting coordination requirements into modes of organization that embody the coordinative structures among entities necessary for the facilitation of the control mechanisms of technical functions. Hence, assuming technologies are given, like with technical roadmaps to future renewable energy systems, we can use 'coherence' as a design principle to estimate the coordination requirements (and modes of organization) of future renewable energy systems.

[82] Throughout this section we refer to the Künneke et al. 2008 article. This is however the working paper which was later published in the Journal of Economic Behavior & Organization under the same title in 2010.

[83] These modes of organization of Künneke et al. should not be confused with the organizational structures this research seeks. Modes of organization relate to the coordination requirements only and miss the other aspect of organizational structures, the involvement and responsibilities of entities.

Figure 4.1 The step-wise progression from technologies to modes of organization



Regarding the first step, Künneke et al. start by discussing the literature on open and closed control systems (Künneke et al. 2008, 6-9). Classifying infrastructures as closed control systems[84], the authors match their definition of technical criticality with the characteristics that closed control systems point to.[85] Thus they identify control mechanisms as critical if they imply a) a significant technical scope of control and are unique (no alternative control mechanisms exist that perform similar tasks)[86] and b) strong time constraints (what is the necessary speed of adjustment to perform the feedback loop in closed control systems) (Künneke et al. 2008, 9). In other words, the criticality of the four technical functions is determined by the scope of control involved and speed of adjustment required.

Three scopes of control are identified by Künneke et al. (2008, 15): the system, subsystem, and component level. The system level encompasses "the most far reaching technical complementarities between its elements, i.e. the nodes and links of the network" (Künneke et al. 2008, 15). The subsystem "constitutes a technically separable part of the overall system" that is able to perform independent services, but

[84] Künneke et al. (2008, 7) define closed control systems as those systems that "are characterized by a feedback loop between the actual and desired performance and the ability to adjust system performance in case of intolerable differences between both." In contrast, open control systems are "based on the assumption that the relation between input and system performance is sufficiently stable to satisfy expectations, while ensuring the technical functioning of the system" (Künneke et al. 2008, 6).

[85] Nightingale et al. (2003, 484) state in this regard that there "are two main ways in which controls are exercised to improve system performance […]. First, in open-loop control an actuating device directly controls the inputs to the components and ensures that they are within the correct range required to produce the desired outputs […]. Secondly, in closed-loop control the output is measured and a feedback loop is used to compare this measurement with its intended output."

[86] System scope involves the "opportunities to actively influence important technical system parameters and […] performance" and "the degree of technical interdependence of the various nodes and links" (Künneke and Finger 2007 CRNI). In other words, system boundaries may be determined by limits of control or the full extent of interconnectivity of the network.

is interconnected with the larger system through a technical gateway. Good examples are local and regional networks. The component level then identifies the various components of infrastructures. Focus is on individual nodes and links. Examples are pipelines, trucks, or production facilities.

Four speeds of adjustment are identified by Künneke et al. (2008, 16): the immediate, short, medium, and long term. The immediate term (T0) relates to the "[o]perational balancing of the control system, under the condition that all technical and organization parameters are given" (Künneke et al. 2008, 16). Here the system needs to respond to unexpected technical disturbances in seconds or minutes. The short term (T5) relates to capacity utilization. Resources are dedicated or relocated for production and transportation processes can be changed insofar the use of existing network capacity is concerned.[87] This hence occurs "under the same assumptions as in T0, but in addition the operation of the technical process can be altered or modified" (Künneke et al. 2008, 16). Decisions are made in hours or days. The medium term (T15) revolves around capacity allocation, which takes place under the same assumptions as T5, but where "the resources that are needed to facilitate the technical process can [now] be allocated" (Künneke et al. 2008, 16). There is an opportunity to deploy technological and organizational variety; new production facilities and network capacity can be built and/or old assets may be reallocated. The time frame is months and years. In the long term (T50), the entire technical process may be redesigned, effectively allowing for the renewal of all infrastructure elements up unto new end-use applications. This "[s]ystem innovation and/or transformation [occurs] under the same assumptions as in T15, but in addition the reference values with respect to the expected technical performance of the system are changing" (Künneke et al. 2008, 16). Designing a new control loop is typically a long-term process of several decades.

Combining the three scopes of control and four speeds of adjustment, twelve combinations can be imagined. Basically, the criticality of technical functions increases when they have to be performed upon shorter notices and on larger scales. For example, in terms of time, operational real-time balancing requires immediate response to developments, whereas the setting of norms and standards for interoperability may be allowed to take months or years. The same goes for the scope; many "functions cannot a priori be restricted to certain parts of the network" [and there may be] insufficient technological means to isolate the performance of single parts of [energy] systems from possible disturbance of neighbouring systems" (Künneke and Finger 2007, 312-313). In turn, it can be stated on a general level that "coordination requirements become more stringent the larger the technical scope of control and the shorter the time period to react on disturbances" (Künneke et al. 2008, 13).

Key in the second step is the concept of critical transactions. Where transactions are defined as the "transfer of 'rights to use' goods or services across technically separable interfaces" (Künneke et al. 2008, 11), critical transactions are those transactions that

[87] For example, while production facilities and distribution means are given, the amount of gas produced and passing through the network is flexible; there is a choice to produce more or less and a choice to produce for spot markets.

are essential to accommodate the control mechanisms of critical technical functions.[88] To understand which transactions are required by the categories of control mechanisms, Künneke et al. study transaction cost economics.

Transaction cost economics (TCE) pertains to how "specific types of transactions can best be coordinated in specific types of governance structures" (Finger et al. 2006), i.e. focuses on the "ex-post costs that result from the contracting and searches for the most efficient governance structure" (Groenewegen et al. 2010, 119). Transaction costs involve such costs as finding information about products and markets (search costs), drafting or negotiation costs, monitoring and enforcements costs, etc. (Groenewegen et al. 2010, 119).[89] Governance or organizational structures are crucial in this respect because they can reduce transaction costs by providing an operating framework for economic exchange. Governance structures such as markets, firms, and state-owned enterprises embody a certain set of rules, regulations, standards, and procedures that address property rights issues, reduce risks, create transparency, and provide means of oversight and arbitration for example. In TCE it is all about what the optimal governance structure to minimize transaction costs is, given the institutional environment of values and norms, given the preferences and attributes of the actors, given the technology, and given the broader political and legal structures (ceteris paribus). In this endeavor, a general distinction is made between governance structures based on their public or private nature and on the level of vertical integration, whereby the combinations of private contracting and public organization represent the two extreme ideal types within which intermediary possibilities may lie.[90]

What decides then whether the governance of transactions should be private or public, vertically separated or integrated? Basically, "economic actors replace markets for hierarchies by integrating transactions into the hierarchy (vertical integration) when it is efficient to do so, i.e. when transaction costs are lower" (Finger

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[88] The authors distinguish two dimensions that make up critical transactions: "a systemic dimension, which relates to the technical scope of control and the speed of adjustment of critical technical functions; and an organizational specific dimension, which concerns the organizational needs to meet the technical system requirements" (Künneke et al. 2008, 12). The former, as we have just seen, refers to the characteristics of the control mechanisms that facilitate the technical functions. The latter concerns the "critical effects related to the way the economic viability of the system is organized" (Künneke et al. 2008, 14). In the end "both the systemic and organizational dimensions should align in their coordination of critical transactions" (Künneke et al. 2008, 14-15) to ensure infrastructure reliability.

[89] Transactional economics exist if coordination gains outweigh internal incentive costs. Transaction costs correspond mainly to "coordination costs, i.e. to cost reflecting the design, the negotiation and the enforcement of contracts between buyers and sellers [and] the market imperfections at the production stage that may result in an inefficient combination of inputs at the downstream stage" (Garcia et al. 2007, 794).

[90] Static blueprints from low to high complexity and private to public ordering are: A) spot market / classical contracting; B) relational contracting; C) private hierarchy / firm; D) regulation of private owner / operator; E) separation of ownership and operators; F) state ownership and private franchises; and G) the state owns and operates (Oration Groenewegen, 2006).

et al. 2006, 5).[91] TCE points to a number of factors that together map the characteristics of a transaction: asset specificity, uncertainty, and opportunities for strategic behavior (frequency of transaction). The specific mix of these factors determines whether a market oriented approach (private contracts) is best suited or whether a hierarchy oriented approach (from private firm to public organization) is more efficient in terms of transaction costs. The reasoning is the following: when asset specificity increases, risks become bigger, or opportunities for strategic behaviour increase (or frequency decreases), transaction costs rise and a hierarchical organization (vertical integration) is increasingly more efficient. In other words, "market contracts are suitable for transactions that do not demand complex negotiations between parties, whereas hierarchies refer to transactions that are highly complex and which call for complicated negotiations" (Finger et al. 2006, 5). This is to say that simple transactions allow actors to include all uncertainties into a contract (which is then able to provide solutions and dispute settlement for all eventualities), while complex transactions do not allow for that, hence becoming inefficient in coordinating actors and favoring vertical integration.

In their 2008 article, Künneke et al. adapt these insights from TCE to infrastructures. They propose to write the scope of control and speed of adjustment that the control mechanisms of technical functions may involve in terms of their transactional characteristics (asset specificity, uncertainty, and opportunities for strategic behavior). They then use the transactional characteristics' relation to more or less centralized forms of organization to differentiate between top-down central control (hierarchies) and bottom-up interaction among autonomous entities as the two extreme ideal-type forms of coordination that may be required to facilitate technical system operations.[92] As such they identify the following actions as coordination requirements: directive intervention, coordination, and corroboration for the system, subsystem, and component scope respectively; and supervision, monitoring, facilitation, and planning for the immediate, short, medium, and long term respectively.

They reason in the following way. "Critical transactions at the system level require directive interventions in order to guarantee the technical complementarities that are essential to safeguard the reliability of the infrastructure system" (Künneke et al. 2008, 18) because investments are very specific and uncertain and opportunities for strategic behavior exist. Subsystems require coordination because they have less unique assets and harbour the possibility to redeploy investments across regions while uncertainty and possibilities for strategic behavior decrease due to the regional confinement of reliability concerns. Finally, the component level focuses on the compliance between system components and the technical requirements of the

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[91] For an overview of the advantages and disadvantages of vertical integration please see Harrigan 1984.

[92] In the original application of 'coherence' the governance of both dimensions was compared and the degree of coherence between them was assessed and related to overall performance. When using it as a design principle, however, the technical dimension is taken as a given and point of departure, while the organizational dimension is open to interpretation, i.e. that which is being designed in order to match the technical dimension.

system. Since asset specificity, uncertainty, and opportunities for opportunistic behavior are low, this level requires only corroboration. Critical transactions in the immediate term (T0) stand for the operational balancing of networks. According to the model of Künneke et al. (2008, 19) the short time span "requires tight supervision in order to force the necessary changes of the technical state of the system." Specific investments to reduce uncertainty and strategic behavior dominate. In the short term (T5), capacity utilization requires the monitoring of the technical operation processes. Here, the technical process can be changed insofar the use of existing capacity is concerned. Asset specificity, uncertainty, and opportunities for strategic behavior opportunities are declining in comparison to T0, but are still considerable; hence monitoring is still required. At T15, capacity allocation is possible (there is an opportunity to deploy technological and organizational variety). There is limited asset specificity mixed with significant uncertainty and possibilities for strategic behaviour. To support system complementarities, some control over resource allocation is hence preferable. This necessitates facilitation. At T50, system transformation and/or innovation takes place. Here the reference values and expectations of infrastructure performance are changing. This means very low asset specificity due to many alternative investments, but high uncertainty. Some careful planning is required to maintain complementarity along the supply chain.

With the coordination requirements of the scopes of control and speeds of adjustment established, we can finally start to express the control mechanisms of critical technical functions in terms of modes of organization. Modes of organization represent the sum of coordination requirements of control mechanisms and at the same time present the interactive or coordinative structures among entities necessary to address these same coordination requirements. In other words, modes of organization enable the facilitation of control mechanisms, i.e. "guarantee the coordination of transactions related to critical technical functions" Künneke et al. (2008, 235).

Establishing modes of organization entails combining the coordination requirements of the scope of control and the speed of adjustment of the control mechanisms. For example, when a technical function needs to be addressed on the immediate term (T0) and involves system-wide operations, the combination of the required supervision and directive intervention results in a mode of organization of authorative supervision. Another example would be a technical function that involves medium term (T15) capacity allocation and component level corroboration, resulting in a mode of organization of a competitive allocation mechanism. In this way, twelve more or less centralized modes of organization are distinguished by Künneke et al. to ensure the varying stringency of coordination requirements of the technical functions of networks (in light of reliability). The result can be seen in Figure 4.3. By now, the underlying 'logic' between the systemic and organizational dimensions should be clear: technical operation becomes more critical (i.e. has more stringent coordination requirements) the larger the scope of control involved in and the shorter the speed of adjustment (the time to respond) required by the control mechanisms of critical technical functions, while higher levels of criticality necessitate more central coordination and hierarchical modes of organization (in contrast to more decentral coordination and bottom-up oriented approaches to organization for lower levels of criticality). In short, higher levels of criticality in the technical functions match more centralized forms of coordination while lower levels of criticality in the technical dimension allows entities to operate more autonomously. To conclude, with the notion of modes of organization, Künneke et al. provide a bridge to cross the gap between the coordination requirements set by technical operations and the coordination possibilities inherent in organizational structures of infrastructures.

Figure 4.2 Modes of organization to secure critical transactions

Scope of control / **Speed of adjustment**	**System** *(requires directive intervention)*	**Subsystem** *(requires coordination)*	**Component** *(requires corroboration)*
T_0 Operational balancing *(requires supervision)*	Authoritative supervision ['system operator']	Collaborative supervision ['system regulator']	General framework conditions ['system norms and standards']
T_5 Capacity utilization *(requires monitoring)*	Compulsory monitoring and enforced adjustment	Mutual monitoring and stimulated adjustment	Self monitoring and voluntary adjustment
T_{15} Capacity allocation (*requires facilitation)*	Controlled allocation mechanism	Guided allocation mechanism	Competitive allocation mechanism
T_{50} System transformation and innovation *(requires planning)*	Directive planning	Indicative planning	Decentralized planning

Source: Künneke et al. 2008, 17.

To sum up, we can derive the degree of central coordination required by classifying the critical technical functions' control mechanisms into their respective scope and speed and relating them into their transactional characteristics. However, one must be very cautious. It is unlikely that each critical technical function fits neatly into one of the twelve modes of organization. This is because the various subcategories of the critical technical functions, often related to either facilitation or planning, involve different speeds of adjustment or scopes of control and require multiple distinct modes of organization.[93] Interoperability, for example, may include all entities when setting system standards in the long run, but adherence may be an immediate issue for individual entities. Consequently, it seems prudent to execute this step of the framework to each subcategory instead of each technical function to get a more detailed and accurate picture of the coordination requirements. While we will do so in further framework applications, we will also need to be able to come to an overall sense of criticality or coordination requirements per technical function to continue in step 4 with finding an organizational structure on a more aggregate level (without getting lost in the details).

To manage the level of detail and be able to state something about the coordination required by a single technical function, we propose to a) differentiate between six degrees of central-decentral coordination and b) focus on the immediate issues of facilitation over those longer-term issues of planning and on those matters that are of more systemic proportions. As for the former, Figure 4.2 exhibits six shades of grey to indicate various levels of criticality[94] next to the twelve modes of organization. These six shades sum up the degree to which critical technical functions require central coordination in order to ensure their functioning and as such represent the criticality underlying the various modes of organization. This implies that one should not blindly copy the modes of organization's terminology as it is meant to represent more broadly the actions that are required for the variety of conditions under which technical functions need to operate. For example, sometimes a mode of 'compulsory monitoring and enforced adjustment' might not seem to fit certain interoperability issues, but the underlying criticality still matches. While we will try to pinpoint each mode of organization in the execution of this step, discussing nuances when necessary, it should always be reminded that these modes need to be broadly interpreted as categories of criticality to get a rough idea of coordination requirements. Please note that we intend to move straight from categorizing the scope of control and speed of adjustment of control mechanisms to the required mode of organization and that we take the above discussion on transactional characteristics and coordination requirements for granted in order to smoothen the application of this step. In any case, let us clarify what these shades roughly imply.

First, issues on the component level at T15 and T50 are considered to be not critical. This is when autonomous entities act according to their interests and take care

[93] While this creates the image that the outcome is predetermined, i.e. that the subdivisions are directly related to the speed of adjustment involved, this is not so. It is not clear, for example, whether the immediate or short term or the medium or long term is required, or whether a certain aspect of a technical function is relevant for an infrastructure at all for that matter.

[94] This definition of criticality hence differs from the technical criticality discussed earlier in section 4.1.1 which implied those aspects of technical operation that are more critical than others for ensuring system functioning, i.e. the critical technical functions. Here criticality implies the degree to which these critical technical functions require central coordination in order to ensure their functioning.

of their operational responsibilities as they see fit and the system operates reliably as a whole. Second, issues on the component level at T5 and subsystem level at T50 are considered have low criticality. Here, entities still take care of their operational responsibilities autonomously, but they voluntarily adjust their actions to a common operational rule and changes therein. Third, issues on the system level at T50, the subsystem level at T5 and T15, and the component level at T0 are considered to be of medium criticality. Operation is done commonly / collaboratively by all involved entities and is based on a mutual agreement on tasks and procedures. This likely involves much regular coordination between, what are in principle, autonomous entities. Fourth, issues on the system level at T15 and the subsystem level at T0 are considered to be of high criticality. Responsibility in this situation is located in a few key entities that function as operational centers that continuously coordinate or attune their actions directly to one another while none of them has authority over the other, but from which other less relevant entities may be autonomous. Fifth, issues on the system level at T5 are highly critical. A central coordination center executes its own operations and monitors those of other entities whose actions affect, contribute / support, or co-manage its function and who may or may not be vertically integrated with it (entities becoming departments). Sixth, issues on the system level at T0 are the most critical. Here, a central coordination center dictates and supervises operations of a technical function across the infrastructure in a top-down and integrated fashion.

As for the latter, we intend to focus on matters of facilitation rather than planning when it comes to establishing the overall mode of organization needed. This is mostly because they represent daily operational practice rather than more distant future developments. This does not mean that future planning should not be addressed. It is to say, however, that because of the higher urgency of more daily operational responsibilities, coordination should be attuned towards them rather than matters further away in the future. The same goes for focusing on matters of systemic rather than subsystem or component level. The potential size of failures simply matters. Due to these foci, overall coordination needs of critical technical functions match those of the most critical of the subdivisions. Table 4.3 presents an example.

Table 4.3 Example of criticality per technical function for a given energy system

	Interoperability	Interconnection	Capacity management	System management
Coordination requirements	-/+	++	++	++

Legend: 6 degrees of criticality / central coordination requirements can be distinguished:

- - - Not critical; autonomous entities act without need for coordination.
- - Low criticality; autonomous entities that voluntarily adjust operation to a common rule/goal.
- -/+ Medium criticality; common operation based on agreement between autonomous entities.
- +/- High criticality; continuous coordination between key entities.
- \+ Very high criticality; central coordinating center that monitors and responds.
- ++ Most critical; central coordinating center that dictates and supervises.

4.1.3.2 Additional Considerations; Infrastructure Features

Relating control mechanisms to transactional characteristics and subsequent modes of organization provides an opportunity to bridge the gap between technical operational characteristics and the coordination necessary for facilitating them. Yet the focus on control mechanisms does obscure a number of important infrastructural features and considerations that affect the ability of control mechanisms to ensure reliable system operations and that may alter the criticality of technical functions and/or degree of central coordination required.

Normal Accident Theory provides some interesting insights regarding interactive complexity and system coupling. Normal Accident Theory outlines a "theory of systems and their potential for failure and recovery" (Perrow 1999, 62; De Bruijne 2006, 53). It portraits technical failures from a systemic perspective yet focuses on their organizational causes. Perrow claims that large-scale failures occur when systems experience multiple failures in design, equipment, operators, procedures or environment. It is when the many aspects interact in unanticipated ways that system designs and operators face a cascade leading to system failure.[95] In this light, Perrow distinguishes two main systemic characteristics, interactive complexity and coupling, that largely determine system reliability. Interactive complexity concerns "the ability of parts of a system to interact in an 'unanticipated' manner" (De Bruijne 2006, 54). Perrow (1984) distinguishes large-scale technical systems "on a scale ranging from predictable, linear interactions to unanticipated, highly complex interactions" (De Bruijne 2006, 54). In the words of Hopkins (1999, 94-95), "[l]inear interactions are those in expected and familiar production or maintenance sequence, and those that are quite visible even if unplanned. Complex interactions are those of unfamiliar sequences, or unplanned and unexpected sequences, and either not visible or not immediately comprehensible." In other words, they create uncertainty regarding how we may expect technology to behave. The coupling of a system concerns the degree to which there is a technical "slack or buffer or give between two items" (Perrow 1999, 89-90; De Bruijne 2006, 54).[96] Large-scale technical systems may be loosely or tightly coupled, depending on how their parts are interconnected. Basically, a system is tightly coupled when events in one part of a system affect another part with little opportunity for human intervention (Hopkins 1999, 95). Highly automated systems often fall in this category. In contrast, in loosely coupled

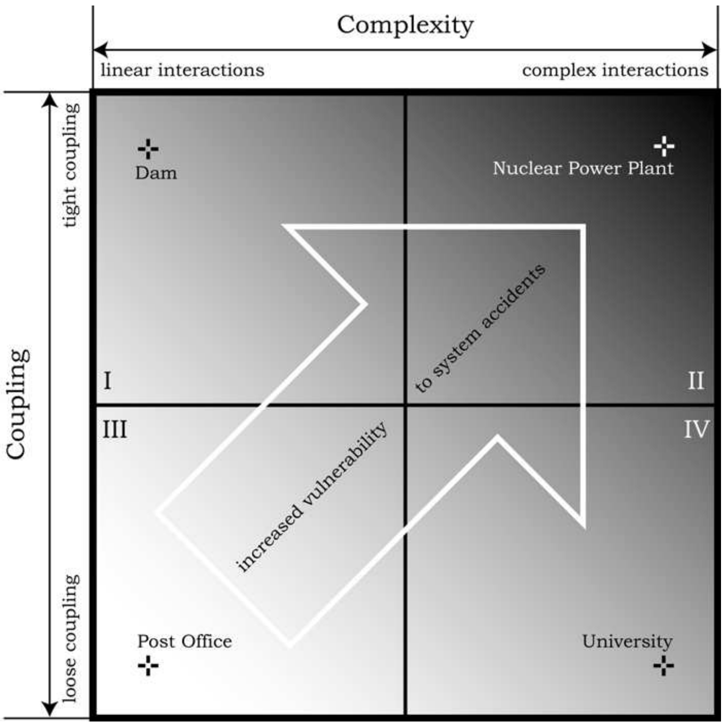
[95] "NAT claims that size and scope also influence the propensity for failure: [A]s systems grow in size and in the number of diverse functions they serve, and are built to function in ever more hostile environments, increasing their ties to other systems, they experience more and more incomprehensible or unexpected interactions. They become more vulnerable to unavoidable system accidents" (De Bruijne 2006, 54).

[96] For example, an electrical power plant and its natural gas supply pipeline form a tightly coupled pair. "In particular, if the gas-fired generator has no local gas storage and cannot switch to an alternative fuel, the generator is very tightly coupled to the gas pipeline. Disturbances in the gas supply will have almost immediate effects on electrical generation" (Rinaldi et al. 2001, 19).

systems "things develop more slowly, […] different outcomes are possible and there is plenty of time and opportunity for human intervention to deal with problems before they become serious" (Hopkins 1999, 95).

Perrow (1999, 93) utilizes both characteristics as two largely independent dimensions to plot the propensity for a large-scale technical system to have failures. Figure 4.3 shows the resulting matrix. Put simply, the more tightly coupled and complexly interactive a technical system is, the higher its propensity for failure. Yet because it is likely that small-scale failures cascade into massive breakdowns in such systems, massive breakdowns should be expected and not treated as acts of God. In other words, such a system is 'normal accident prone'; one that predictably fails, but in unpredictable ways (De Bruijne 2006, 54).

Figure 4.3 Mapping the propensity for failure in large-scale technical systems



Source: Perrow 1999, 332.

What makes this matrix interesting for our research is that Perrow links these dimensions to more centralized and decentralized coordination requirements or 'authority structures' (Perrow 1984). On the one hand, systems with a high degree of interactive complexity require more decentralized management, because "[d]ecentralized units are better able to handle the continual stream of small failures" (Perrow 1999b, 152). When a system is complex, "central decision makers will not be in the best position to comprehend what is going on and local decision makers may be better placed to avoid system failure" (Hopkins 1999, 97). In such situations, autonomous decision making is favored. On the other hand, tightly coupled systems "must be operated through a highly centralized authority structure, with operators reacting immediately using predetermined SOPs" (De Bruijne 2006, 57). According to Perrow (1999b, 152), "[d]ecentralized systems are too slow to respond to widespread multiple failures because the units cannot be instantly and unquestioningly controlled from the top where often there is a superior view". In other words, when a system is "tightly coupled and there is little or no time for reflection on the job, authority must be highly centralised with operatives doing what they are supposed to do in a pre-determined and unquestioning manner" (Hopkins 1999, 97). Hence there is an inherent conflict in the authority structure and management style of complexly interactive and tightly coupled large-scale technical systems; they require both decentralized and centralized modes of organization to run safely and reliably. This had led NAT theorists to be pessimistic of our ability to avoid disasters. Unfortunately, infrastructures seem to fall into this category.[97] Some, however, point to the fact that it is possible for authority to be simultaneously centralised and decentralised. Shrivastava et al. (2009, 1367), for example, point out that "it may be possible to ensure that decision-making migrates to where the action is." Hence in otherwise bureaucratic, centralized organizations, it might be policy to relocate authority to the frontline part where a failure is occurring in order to be able to rapidly respond and avoid a larger disaster. Thus the predicament of highly complex and tightly coupled systems might not be as dire as NAT theorists believe it to be.

Discussing NAT without referring to the literature on High-Reliability Organizations (HRO) would not do justice to the academic debate on reliability in organizations. The key difference between both is that NAT considers serious accidents and disasters as inevitable in highly complex and tightly coupled systems or organizations, because they are inherently susceptible to serious accidents (Perrow 1984; Rijpma 2003). In contrast, HRO proponents (La Porte and Consolini 1991; LaPorte 1996; LaPorte and Rochlin 1994; Rochlin 1996; Rochlin et al. 1987; Roberts 1993) feel that accidents are preventable by managerial strategies, pointing to examples of organisations that have achieved outstanding reliability and safety records despite the hazardous technologies they deploy (examples are aircraft carriers, submarines, nuclear reactors, air traffic control, and space shuttles). A few managerial strategies to mitigate risks are discerned. High reliability organizations, for example, subject their personnel to intense training so that they are able to respond quickly and adequately to contingencies (without senior supervision or approval (Rijpma 2003, 39), use redundant assets to back up failing parts or persons, decentralize decision-

[97] A word of caution: so far, Normal Accident Theory (NAT) "has seldom been applied to infrastructure industries, even though Perrow (1999a:97) and other scholars (e.g. Weick, 2004:28) rank infrastructure technologies (electricity grids, rail transport, airways) as tightly coupled, yet mildly complexly interactive in the complexity and coupling matrix" (De Bruijne 2006, 56). Hopkins (1999, 95) also notes in this regard that NAT is only limitedly relevant: "it is not an explanation for disastrous accidents in general but only those which occur in complex, tightly coupled systems." Many disasters, such as the Bhopal accident, space shuttle disaster, Chernobyl, or the Exxon Valdez spill are not part of it.

making authority, create buffers and apply the concept of conceptual slack[98], and understand the value of learning, similations, and extensive trial and error (Rochlin et al. 1987; Rochlin 1989; La Porte and Consolini 1991; Roberts 1993; Rijpma 1997; Pidgeon and O'Leary 2000; Turner and Pidgeon 1997). Other important factors are a strong culture of vigilance, careful attention to design and procedures, and a strategic prioritization of safety and reliability (Shrivastava et al. 2009; Weick et al. 1999).

In the end, both theories seem to differ in their approach to the issue of reliability of organizations. Whereas NAT focuses on structural organizational determinants that make the operation of an organization's technical system more or less prone to failures, HRO focuses on what organizations (as firms, i.e. agency) may actively do in terms of managerial strategies to prevent major accidents. While the debate does not have a clear 'winner', in his comparative test of both theories, Sagan points to a number of near-accidents that could have escalated in spite of all the efforts to create reliable operations in relevant organizations had the circumstances been slightly different (Rijpma 2003, 40). "[I]t was less good design than good fortune that prevented many of the accidents from escalating out of control" (Sagan 1993, 267-268). For this research, the organizational or structural focus of NAT, mostly its concepts of interactive complexity and coupling, makes it far more relevant than HRO.

So what can we learn from NAT? First, the concept of interactive complexity urges us to introduce complexity and intensity as considerations that represent infrastructure features and that affect the ability of control mechanisms to facilitate reliable operations. Although the concepts seem similar to the scope of control and speed of adjustment in the sense that both complexity and scope increases seem to coincide on the one hand and that intensity increases seem to shorten the speed of adjustment on the other, there is more to it than that. Complexity and intensity can also increase while network scope and speed of adjustment remain the same. The complexity of networks, for example, can increase when the number of entry and exit points grows, when one moves from a single and constant gas quality to multiple and diverse gas qualities, or when the network starts to include more functions, e.g. using the gas network as storage for electricity. Then more different energy flows have to be facilitated by the same network. This aspect is not truly covered by the current definition of the scope of control which focuses more on a functional rather than a physical distinction. Another example is the fact that the intensity or the volume of energy that flows through the grid can increase while the speed of adjustment remains the same. McCarthy et al. (2007), for example, point to the degree of capacity utilization, i.e. the degree to which a network is utilized, in light of network reliability. If we were to use a certain grid more intensely, control mechanisms for operational balancing and tactical capacity management may remain the same at first glance, but may also necessitate closer monitoring and involve shorter reaction times because there is less leeway when handling failures. In this sense, intensity of use may well be

[98] To prevent hasty action on questionable beliefs or convictions, organizations maintain diverging managerial styles for prolonged periods of time before deciding which one to follow (Rijpma 1997, 17; Schulman 1993). This helps them not to overlook important procedures in managing activities.

because of a lack of redundant assets. Low degrees of complexity and intensity may thus lessen criticality while high degrees may increase it. In the end, these concepts help to nuance the coordination requirements of technical functions' control mechanisms.

Second, there is an important difference between NAT and the coherence literature that needs to be discussed. Whereas Perrow equates higher levels of interactive complexity with the need for more flexible, decentral forms of organization, the literature on coherence rather considers high levels of interactive complexity to require more central coordinative structures. Thus, while both NAT and the literature on coherence agree that increasing interactive complexity leads to a higher propensity for failure (see also Amin 2001 and 2002), i.e. raises criticality, they differ as to how it should be addressed. Whereas NAT argues that uncertainty and unpredictability in interactions requires flexibility to be able to quickly respond to failures[99] (along the notion of self-organization), the coherence literature follows the logic of transaction cost economics that poses that uncertainty is best addressed by vertical integration or other ways to limit risks (like government guarantees or risk sharing). What makes the matter murkier is that Perrow is not always clear about what constitutes a complex, tightly coupled system (Hopkins 1999, 96).[100] There is considerable room for interpretation. Perhaps the best perspective is to see the difference between NAT and coherence literature as similar to the difference in dealing with small and big failures. Great flexibility helps to quickly deal with many local and smaller disturbances before they spread. Dealing with big failures, in contrast, requires a larger scope of control, one that preferably covers the whole network. Of course, in practice both central coordination and flexibility are needed; the division of labor between transmission and distribution network companies is a case in point, as we will see in chapter 5. Though it is tempting to focus only on the bigger failures, because the literature on coherence focuses on the critical technical functions and not all functions, one cannot simply ignore the issue. What about the need and possibilities for flexibility in infrastructure operations in the face of central coordination requirements? One should not simply equate higher complexity with more centralized coordination needs. There might be circumstances in which higher criticality may necessitate more flexible decentral coordination. Unfortunately, both NAT and 'coherence' do not tell what these are.

Third, the concept of coupledness enhances our understanding of system reliability and the need for buffers. When a system is loosely coupled, it is generally considered to be less critical by Perrow because buffers manage the interface between network components and thus may prevent cascading effects throughout the whole system. The buffer allows for decentral coordination; if one entity has a failure, another may not be affected by it. Tightly coupled systems in turn may be more prone

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[99] De Bruijne (2006, 55) states in this regard that the interactive complexity and tight coupling of large systems poses obvious problems for their operation; they simply may "extend beyond operators' capability to anticipate and understand sequences of events and properly react once a failure occurs somewhere in the system."

[100] As Kates (1986) pointed out, "the absence of clear criteria for measuring complexity and coupling makes [Perrows] examples seem anecdotal, inconsistent and subjective."

to the negative effects of interdependencies among entities (Amin 2001 and 2002). However, they also generate the benefits of such interdependence: faster network flows and economies of system. So there is an operational and economic trade-off between reliability and efficiency here. Considering our focus on the former in this research, we may equate tightly coupled infrastructures with a higher propensity for failures and more central coordination requirements than loosely coupled systems. Hence, when assessing the control mechanisms of technical functions of future renewable energy infrastructures, we need to analyze whether they will operate in a more tightly or loosely coupled environment in order to nuance the degree of central coordination required upward or downward.

In sum, these features of energy infrastructures - system complexity, network traffic intensity, need for flexibility, and the degree of interdependence between entities (coupledness among components) - must be considered when assessing the coordination requirements of control mechanisms, because they affect their ability to ensure reliable operations. The next question is then how to weigh them; in how far should they alter the coordination requirements of a technical function? There is no straightforward answer. It is not only a highly situation specific matter, but also not an exact science. We will therefore discuss how these features are likely to affect coordination requirements during the application of this step of the framework.

4.1.4 Putting the Organizational Structure Together

The results of steps two and three need to be brought together in order to generate the required overall organizational structure. Whereas step 2 provides us with an idea of which entities are involved (and to what extent) in the facilitation of a particular technical function, step 3 sheds light on the coordination requirements among the entities involved for that technical function (and the mode of organization that should take care of them). Two questions remain however. First, which combination of entities' involvement and coordination requirements leads to what organizational structure for a specific technical function? Second, how to integrate the required organizational structures of each of the four technical functions into one whole?

Regarding the former, we need a way to combine the responsibilities of entities in the technical operation of a future energy system with the degree of central coordination required by the control mechanisms of the various technical functions and link the resulting combinations to the organizational structures identified in chapter 2 (vertical integration, lead entity, common operation, and incidental coordination). Yet, how to deal with the complexity of the emergent combinations or possibilities? There are simply too many possibilities if one combines the various entities that may be responsible (one, few, many, all), not to mention the amount of representatives of a particular entity, and the various coordination requirements that may be involved (the levels of criticality). To move forward, we propose to simplify the allocation of responsibilities into categories of whether there exists an entity that is significantly more involved than others or whether multiple entities are roughly equally involved in the facilitation of a technical function[101] and to simplify the coordination requirements of technical functions into strong and weak (central and decentral coordination). This way, we may identify four resulting combinations that in turn can be linked to the four organizational structures as defined in chapter 2. Basically, if centralized coordination is required for a technical function and a single entity stands out as the most responsible, then the structure of a lead entity that takes command seems fitting. If, however, centralized coordination is required but many entities are involved roughly equally, then vertical integration seems best suited to avoid the complexity of the necessary interactions. Next, if criticality is low and a single entity is responsible for a particular technical function, incidental interaction among autonomous entities seems sufficient as coordination is likely to be only occasionally required (if at all). Finally, the combination of low criticality and multiple entities that are roughly equally involved seems to be best facilitated through common operation based on mutual agreement between autonomous entities. The result can be seen in Table 4.4 below. Of course, this is very black and white, and outcomes may not represent the four ideal-types neatly in practice, but it nevertheless presents a reasonable yardstick or guiding reasoning. In the end, a balance needs to be found between the ability to discuss possible combinations at the hand of a few ideal-types so as to keep an overview and not get lost in endless possibilities on the one hand, and retaining a certain degree of detail that does justice to important differences in organization and prevents straight-jacketing outcomes into prefixed categories on the other. If the four combinations prove dissatisfactory in application, we might consider more categories such as whether there are one, two, or three or more entities involved and whether coordination requirements are weak, medium, or strong. Then a three by three matrix of organizational structures appears.

Table 4.4 Finding an organizational structure for a technical function

	Strong coordination needs	**Weak coordination needs**
Multiple entities roughly equally involved	Vertical integration	Common operation
Core entity present	Lead entity	Incidental coordination

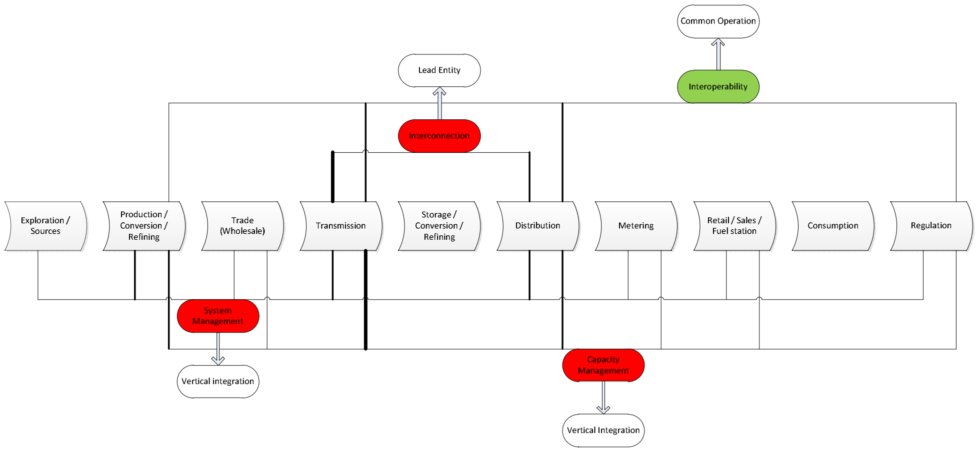
[101] While this combines the question of which entities are involved and to what degree, it somewhat ignores the amount of representatives per entity. It does not separate for example whether there exists a single or multiple transmission network operators when the entity TSO is considered to be the core entity present. However, as we are more interested in vertical linkages (rather than horizontal) between infrastructure entities in this research, considering the overall flow of energy from production to retail, this choice seems a warranted sacrifice to facilitate coming to an overall organizational structure.

Concerning the latter, how to combine the outcomes for each technical function into one whole? What to do when completely different entities are involved and/or when very different degrees of criticality exist per technical function? To cope with such situations, we intend to graphically represent all connections in one supply chain overview (see Figure 4.4) and reinterpret the detailed outcomes of the previous steps on the level of the overall infrastructure. We propose to adhere to the following logic for putting the overall organizational structure together: those entities charged with the critical technical functions that require central coordination should become the core entities in overall infrastructure organization and those that deal with less critical technical functions may be vertically integrated with it, separated from it, or even be completely autonomous, depending on the degree of central coordination required of those technical functions. In other words, we basically look at the more important entities and functions involved (entities with many responsibilities and functions who require central coordination) and move from there to create an overall picture. To illustrate, in the electricity example below, network companies[102] are the entities most heavily involved with the most critical technical functions. Accordingly, leadership in technical operation seems best placed in their hands. This, however, creates a certain 'bias' towards more centralized organizational structures because the overall organizational structure of all four functions is mostly attuned to the most critical technical function.[103] However, to retain high levels of reliability this seems warranted. In the end, the reasoning behind the exercise is the most important. The purpose here is to simplify previous results to come to a workable general picture; the more detailed picture can be seen in steps 2 and 3.

[102] For example, the transmission operator is often the heart of an infrastructure because of the stringent needs posed by operational balancing, while the responsibilities of other entities are often defined in relation to it, though if technically possible they may operate independently from it.

[103] Extending the centralized organization for one technical function to the others might be damaging to the flexibility of operation in those others, but this is still preferable over lacking the coordination necessary for reliable functioning of the one.

Figure 4.4 Towards an organizational structure



Legend: No and indirect involvement = no line
Supportive and weak direct involvement = normal line
Strong direct involvement = bold line
Leading involvement = fat line

Not critical = white
Low criticality = blue
Medium criticality = green
High criticality = yellow
Very high criticality = orange
Most critical = red

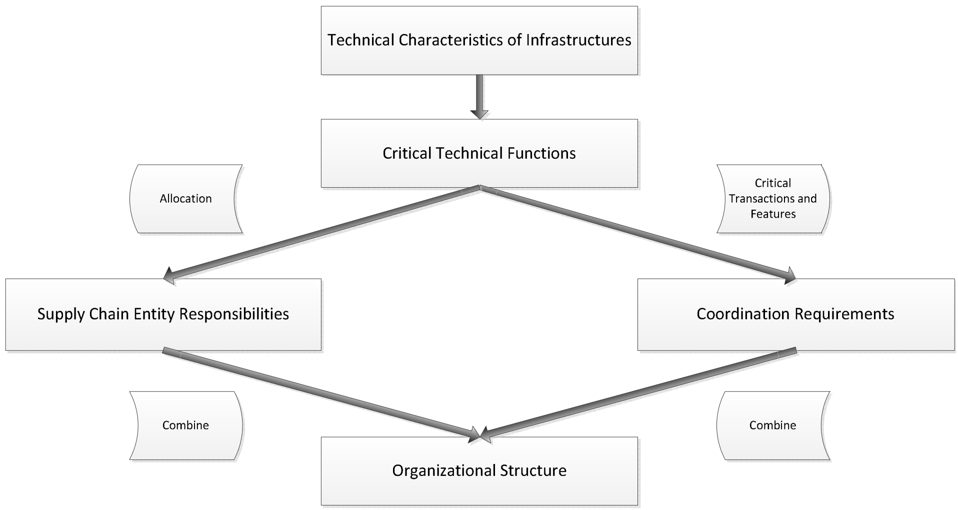
4.2 Possibilities and Limitations of the Framework for Alignment

The framework for alignment seemingly bridges the gap between technological characteristics of infrastructures and the organizational requirements that must be met in order to ensure their reliable functioning. It involves four basic steps once an energy infrastructure and its technical characteristics have been chosen for application:

- Identify critical technical functions and accompanying control mechanisms
    - What reliability problems may arise in terms of critical technical functions?
    - How can these be solved? What is required to overcome them?
- Allocate technical functions to supply chain entities
    - Which entities are responsible for the facilitation of the technical functions?
    - How much are these entities involved (one main or all roughly equal)?
- Assessing coordination requirements
    - What is the scope of control and speed of adjustment of the control mechanisms required to facilitate the critical technical functions?
    - How may infrastructure features affect coordination requirements?
- Combine the outcomes of steps 2 and 3 to come to an overall organizational structure

- To which organizational structure does the combination of entity involvement in and coordination requirements of a specific technical function point?
- What organizational structure might encompass all operational requirements?

Figure 4.5 A framework for alignment



The framework of alignment presents first and foremost the possible means to find organizational structures complementary to infrastructure technologies in light of reliability. Next to that, its four steps help to structure the discussion of future energy system technologies around four concrete technical functions, thereby putting technical changes into perspective regarding their effect on system complementarity, and allow us to have some detailed insights into the responsibilities of entities and the relationship between them in the operation of a renewable energy infrastructure. The detailed results are useful for entities wishing to understand their role and responsibilities in a future energy system and the organizational consequences of technical changes, also for making investment decisions. The resulting overall organizational structure found as a result of applying the framework to a case in turn presents policy makers with a possibility to start charting a co-development policy. While the remainder of the research focuses on the exploration, illustration, and refining of the framework, these practical implications will be addressed in chapter 8.

Despite the fact that the framework of alignment allows us to identify complementary organizational structures to infrastructure technologies, its use knows some conditions and limitations.

First, the framework focuses mostly on the networks of infrastructures, rather than on energy generation and application. Though one must be aware of this, it is not necessarily a shortcoming in this research with its focus on infrastructure reliability, a term strongly related to the integrity of the physical network. It is important however that the allocation of responsibilities indicates the role of producers and retailers in relation to network functioning. This way these entities are brought into the context of the technical network functions.

Second, the framework entails a static comparative approach that can only provide us with a snapshot of an infrastructure at a certain moment in time. How can it be used for transitions to new technical systems? It needs to be remembered here that a transition is likely to involve a series of technical changes over a prolonged period of time, and that the organizational structure required may change during that period. A simple solution is to compile several snapshots at various stages of a transition. It seems wise to take the various stages of development, as discussed in the transition process, technical life cycle, and infrastructure development model, as a guideline.[104] Putting all the static images together, a roadmap emerges. This entails distinguishing which technologies will be developed and deployed when and using the framework to find the optimal organizational structure for the technological system existing in each of the four phases. The differences in the necessary organization between the phases then account for the organizational changes required when moving from one phase to another.[105]

Third, we need to point out that there is an issue so far neglected. The organizational structure of an infrastructure does not exist in a void, but is supported by institutional arrangements that set the boundary conditions and incentive structure under which infrastructure entities operate. We saw this already in chapter 2 where the social dimension of infrastructures contained both actor and institutional aspects. The addition of institutional arrangements is, however, not dealt with by the framework. At most, it is implied. Though it would go beyond the purpose of this research to include institutional arrangements, it should be possible to add an additional step in the framework after the fourth that investigates which institutional arrangements might be required to enable and constrain infrastructure entities in their efforts to organize for reliability. New Institutional Economic literature abounds in addressing questions of competition and regulation in infrastructure industries. More importantly, these insights can be adapted to suit the stimulation of reliability. For example, what regulatory framework is required to ensure that sector incumbents invest in reliability?

Finally, how to deal with information flows in relation to reliable system operation? The operation and nature of future renewable energy systems are strongly

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[104] The timing of the snapshots is an important choice to make to ensure that a useful roadmap emerges from the various static images.

[105] Interesting questions that arise in this respect are whether institutions and technologies are likely to co-evolve and whether emerging 'incoherences', as the result of a lack of co-evolution in the shift from one phase to another, can be 'set right' in a shift to the next phase. Other interesting questions are whether there will be a shift in organizational requirements along the four technical functions mentioned; for example that in the early stages of the emergence of a technological system issues of interoperability and interconnectivity are more critical while later, when the network is mature, capacity and system management issues become more urgent.

related to the possibilities offered by ICT technologies. We saw this already in the solar PV example in chapter 3. Should data management be integrated with the transmission or distribution operators for reasons of capacity management or link all entities? If the latter, who should be in charge? Is a neutral party required to take care of data management? How might the use of ICT facilitate and alter coordination among entities? On the one hand, it may enable opportunities for more decentralized operation. On the other hand, because the data is a strategic asset, it calls for shared management and equal access by entities. By ignoring such issues thus far, the framework thus defined seems biased towards a more mechanical operation of infrastructures. Yet this is only partly true. ICT is present in the framework as an enabling and constraining factor of technical operation, mostly capacity management. The possibilities and impediments of ICT reflect upon possible control mechanisms which in turn reflect upon the division of tasks between entities and the coordination requirements among them. As such, ICT plays a supporting role to the mechanical operation (and is indirectly taken on board). It is this perspective that this research adheres to. The more so because it is doubtful in how far future energy systems are likely to change this supportive role of ICT.

4.3 Conclusion

This chapter developed a framework for alignment; a framework that allows estimating what organizational structures are required for the reliable operation of future renewable energy systems. The core challenge in this endeavor was to translate particular technical characteristics of energy infrastructures into their coordination requirements in light of reliability. Four steps were identified, at the hand of the definition of organization of chapter 2 and a focus on those aspects of technical operation that affect system complementarity and inter-entity coordination. They bit by bit unravel how to express technical characteristics in terms of organizational requirements: first, identifying the critical technical functions and control mechanisms; second, allocating the technical functions by establishing which supply chain entities are involved in their facilitation, to what degree they are so, and how many of a particular entity there are; third, assessing the coordination requirements of (and necessary mode of organization to facilitate) the control mechanisms of technical functions while weighing in several important infrastructural features; fourth, combining the outcomes from the previous two steps into one organizational structure. Let us now see how this framework fares in an exploration on some current cases.

5. Learning by Doing; Refining the Framework

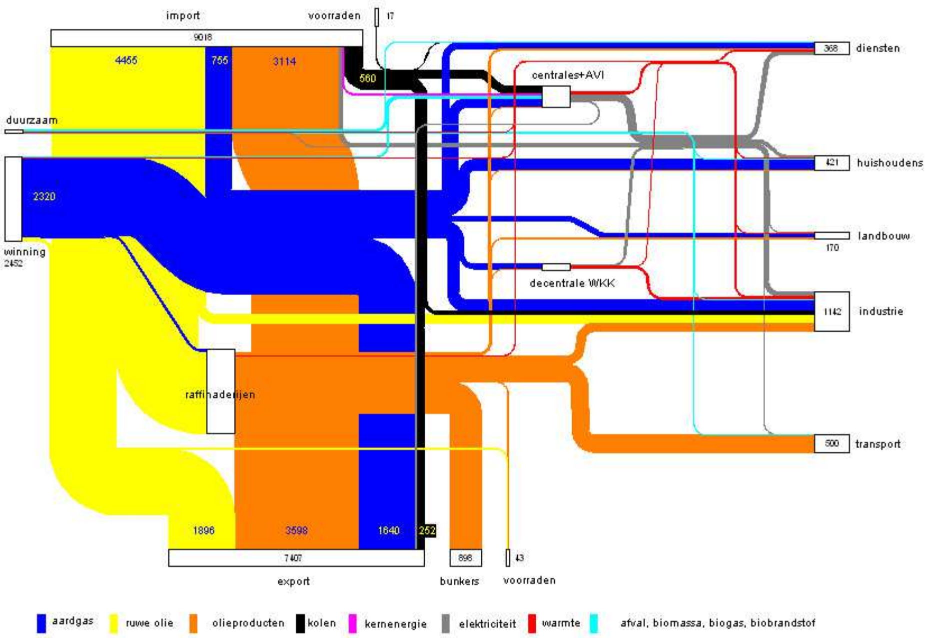
The established framework for aligning organizational structures to technical characteristics of networks provides the possibility of investigating the organizational requirements of new renewable energy systems. Before it is applied to future energy networks however, some further exploration of its applicability and ability to provide accurate outcomes is necessary. This chapter does so by applying the framework to the electricity, natural gas, and petrol sectors in the Netherlands; what are their organizational requirements? These contemporary cases serve to explore the use of the framework, allow us to compare the results of the framework with existing organizational structures in the light of reliability levels, and suggest possibilities for improvement. This 'test' is thus not meant to falsify or prove but rather aims to refine; it should be seen as part of further framework creation. The three main Dutch energy vectors are presented in section 5.1, the framework is applied in section 5.2, and experiences and improvements are discussed in section 5.3. As we will see, the framework is not a panacea; there are some important conditions and impediments to its use that require the addition of certain considerations in order for it to become the framework we seek.

5.1 The Dutch Energy Sector

The Netherlands is a small (41526 km2), densely populated country (16,67 million) in the northwest of Europe, bordering Germany to the east, Belgium to the south, and the North Sea to the west and north (CBS statline, 1-11-2011). The western part is largely urban; the four major cities of Amsterdam, Rotterdam, The Hague, and Utrecht forming an almost interconnected whole, called Randstad, while the north, east, and south are more rural. It is also known as one of the low-countries (or Holland) because it is the estuary of some of Europe's most important rivers such as the Rhine, the Maas, and the Waal and because about 60% of its territory lies below sea level. The rivers play an import role in the country's position as a transport hub for the continent, as they connect the port of Rotterdam to the industrial Ruhr area in Germany. The Netherlands was the 7th largest economy in Europe in 2007 with a GDP of 436 billion (IEA 2009, 15). The Netherlands hosts a large service sector and some important industries, most notably in "food processing, chemicals, petroleum refining and electrical machinery" (IEA 2009, 15).

In terms of energy, the Netherlands' total primary energy supply (TPES) in 2008 was just over 83 million tonnes of oil equivalent (Mtoe), "a 9% increase from 2000 and a 24% increase from 1990" (IEA 2009, 16). The dominant energy sources are oil and gas, representing about 39.6% and 44.2% in the overall primary energy mix (TPES) respectively. The rest is made up of coal (10.3%), combustible renewables and waste (3.9%), nuclear (1.4%), and geothermal/solar/wind (0.5%) according to the IEA (website 23-01-2011). The reliance on fossil fuels is largely due to the discovery of hydrocarbons, mostly natural gas, in 1959. In 2004, Dutch domestic production was dominated by natural gas (92%), followed at a distance by oil (4%), renewables (3%), and nuclear (1%) while net energy imports included mostly oil and coal, representing 80% and 17% of import shares respectively, and some electricity (3%) (EC 2007c). Energy exports are dominated by natural gas and oil, the latter being more a matter of throughput. Total final consumption (TFC) in 2006 was just over 61 Mtoe. The industry accounts for about 40% of consumption, with transport (25%), the commercial sector (19%), and households (16%) trailing not far behind (IEA 2009, 17). Perhaps the most remarkable aspect of the Dutch energy sector is that imports and exports are far greater than domestic production and consumption, with the notable exception of natural gas, which is produced in large quantities. The complexity of Dutch energy flows is captured in Figure 5.1 below. In terms of energy security, the Netherlands' position is generally positive, with the "domestic production of natural gas, its [strategic] position as a transit hub in north-west Europe [especially the Port of Rotterdam's] and its role as a major oil-refining centre in Europe" (IEA 2009, 49). In addition, the Dutch contribute to European energy security by providing storage services to the market and its extensive network of pipeline and transmission connections.

Figure 5.1 Energy flows in the Netherlands in petajoule (PJ) in 2006



Source: energie 2010 website.
Translation: voorraden = supplies; duurzaam = sustainable; winning = exploitation; bunkers = storage; diensten = services; huishoudens = households; landbouw = agriculture; industrie = industry.

The strong presence of fossil fuels seems to go at the expense of renewables. The Dutch lag behind in the EU's average use of renewables. The share of renewables in the overall energy mix of the Netherlands stood at a mere 2.8% of total energy supply in 2007 (IEA 2009, 107) or 2.9% of total primary energy consumption (EREC 2009, 1). This is not only relatively low compared to most European countries, or IEA members for that matter (where the Netherlands ranks as the sixth-lowest of the 28 IEA member countries with respect to the share of renewables in its TPES (IEA 2009, 107)), but it is already an increase of 85% since 2000! Much of the explanation for this low figure lies in the lack of large-scale hydropower in the country. Currently, the largest share of renewables comes from biomass (over 85%), "mainly co-firing in coal plants, with smaller volumes used in small combined heat and power plants (CHP)" (IEA 2009, 107). Second is wind energy with almost 13%. Solar and hydropower take up the remaining, very small shares. Nevertheless, "energy supplies from wind and solar photovoltaics (PV) have been growing quickly since 2000 - more than quadrupling" (IEA 2009, 107). For example, in 2007 renewables and waste made up nearly 9% of Dutch electricity production, an amount that is twice as much as in 2000 in absolute terms (IEA 2009). Regarding biofuels, in 2006 about 0.4% of road consumption came from biofuels, while in 2007 this figure rose to 2% of total fuel consumption in road transport (IEA 2009, 108). In the end, however, 2% is still a marginal amount. Against these low levels of renewables the goal set by the Dutch government, that renewables should provide 20% of total energy supply by 2020, seems overly ambitious, the more so because it goes beyond the proposed national target of 14% of renewables in total energy consumption by 2020 under the overall EU framework.[106]

Institutionally, the Ministry of Economic Affairs (EZ) is the main entity responsible for energy policy (IEA 2009, 18). However, the Ministry of Housing, Spatial Planning and the Environment, the Ministry of Transport, Public Works and Water Management and the Ministry of Agriculture, Nature and Food Quality are also closely involved in energy and environmental policy when it concerns their policy area. For example, biofuels are not only a matter of energy policy of EZ, but also Transport. These entities function as the main financiers, although R&D specifically also involves the Ministry of Education and Science. The guiding policy principles are availability, affordability, and reliability, and increasingly sustainability. Other important entities are the Office of Energy Regulation (*Energiekamer*) and SenterNovem. The Office of Energy Regulation[107] operates as a chamber within the Netherlands Competition Authority[108] and is charged with regulating and overseeing

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[106] The Netherlands has to comply with binding EU targets for total greenhouse gas (GHG) emissions and non-binding EU targets for renewable energy shares in TPES, electricity supply, and transport fuels (IEA 2009, 20).

[107] The Dutch energy regulator, the 'energiekamer', is the "independent public entity that monitors and enforces governments' objectives, especially with respect to network access, network tariffs, and the protection of residential customers" (Finger and Künneke 2007, 15). It also is responsible for issuing supply licences, appointing network operators, determining network access conditions, and undertaking a biannual oversight of the network operator's investment and maintenance of transport capacity (IEA 2009, 19).

[108] The NMa is an autonomous administrative authority (Zelfstandig Bestuursorgaan) since July 2005 and watches over the Competition Act. It enforces the prohibition on cartels, abuse of market power, and assesses mergers and acquisitions (IEA 2009, 19). It is mostly funded by

the liberalised Dutch gas and electricity markets – in which the gas and electricity grids are both owned and operated by independent, state-owned companies unbundled from other parts of the supply chain (TenneT for electricity and Gas Transport Services for natural gas) – according to the Electricity Act and Gas Act (IEA 2009, 19). SenterNovem is the Dutch Agency for Energy and the Environment and the lead responsible for implementing energy policy, promoting sustainable development, and R&D / innovation. It acts as an intermediary between energy users and the government and assists participants on both technical and organizational levels (IEA 2009, 19). Other relevant (intermediary) institutes in this respect are the National Organisation for Scientific Research (NWO) and the Technology Foundation. On the more executing side, the Energy research Centre of the Netherlands (ECN), the largest research center in the Netherlands in the field of energy with about 900 employees, links fundamental research at universities with the testing of practical technical applications, while also providing the Dutch government with energy demand and supply, CO2 emissions, and energy efficiency forecasts (IEA 2009, 20). Furthermore, private companies, universities and institutes, and the Netherlands Organisation for Applied Scientific Research (TNO), are the core executers of government policies. Chapter 6 will deal more in-depth with Dutch transition and renewable policy.

Let us now take a look at the three main energy vectors in the Netherlands (electricity, natural gas, and petrol) at the hand of their supply chain components. The purpose here is to introduce these energy infrastructures and their key technical and operational features to allow for the application and refinement of the framework. It is not our purpose to provide an exhaustive discussion on these sectors or all specific technologies in them.

5.1.1 The Dutch Electricity Sector

The Netherlands' total installed electric power generating capacity was about 25628 MW in 2009. The five largest producers of electricity in the Netherlands (Electrabel 4710 MW, Essent 4760 MW, Nuon 4307 MW, E.ON Benelux 1770 MW, and Delta 715 MW) are responsible for over 70% of installed capacity (IEA 2009, 93). Of the generating capacity, about 74.3% comes from steam turbines and combined heat and power (CHP) – "often owned by smaller companies, including new entrants" (IEA 2009, 87) – , 16% from gas turbines and motors, 7.2% from renewable sources, 2.2% from nuclear energy, and 0.3% from other type of installations (IEA 2009, 87 and 89). Electricity production was 118577 million kWh in 2009. Natural gas accounted for almost 60% of power generation in 2007, with slightly more than 25% coming from coal, 5% from biomass, 4% from other renewables, 4% from domestic nuclear, and about 2% from oil (IEA 2009, 88-89). In the future it is expected that new coal-fired power plants will increasingly replace natural gas-based installations. In addition, 5% of electricity supply is imported. Over the last couple of years, total electricity imports

the Ministry of Economic Affairs, though it also receives some finances from energy companies through permit application fees.

of the Netherlands ranged between "23 to 27 TWh of electricity per year" while exports were lower at 5.4 to 5.9 TWh per year. As such, about 20% of total final consumption is imported each year (IEA 2009, 90).

Wholesale electricity trade is separate from production. The wholesale electricity market is shaped by the contractual arrangements between producers, traders, suppliers, and customers[109] and takes place in a number of markets in the Netherlands: "the bilateral market (forward and spot), the over-the-counter (OTC) market (forward and spot), European Energy Derivatives Exchange (ENDEX) (forward), Amsterdam Power Exchange (APX) (spot), and TenneT (balancing)" (IEA 2009, 92). Commonly, traders buy their energy directly from producers, via energy suppliers, or on the APX (TenneT website 01-02-2011). A number of suppliers and producers have their own exchange; others outsource trade to third parties.

The national electricity network, i.e. the medium- and high-voltage grids (110 kV-, 150 kV-, 220 kV- en 380 kV), spans 259241 km, connects 7926000 customers, and is owned and operated by TenneT. TenneT is a state-owned enterprise that is fully ownership-unbundled from competitive parts of the business (IEA 2009, 91).[110] TenneT holds the decision rights related to the high-voltage transmission grid and is under conduct regulation in order to safeguard independent and non-discriminatory access. Network access is documented in the so-called 'netcode' and is "based on regulated third-party access (TPA) tariffs, in accordance with the Electricity Act"[111] (IEA 2009, 96). As the transmission system operator (TSO), TenneTs tasks include the transport of electricity from producers to users for suppliers, load balancing of the

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[109] According to the IEA (2009, 92-93) "[p]roducers and suppliers can agree to contract specifications among themselves, including the size, duration and term of electricity supplies. Forward contracts are most commonly traded in the bilateral market, but some spot contracts (*e.g.* day-ahead, intraday) are also concluded. Standardised contracts are available in the OTC market and on APX and ENDEX exchanges."

[110] The electricity sector has changed considerably over the last decade due to liberalization and unbundling (Baarsma et al. 2007; Brunekreeft and Van Damme 2005; Damme 2005). Traditionally, "the electricity sector has been strongly vertically integrated between production, high-voltage long-distance transmission, low-voltage distribution, and sales" (Finger and Künneke 2007, 7). Four companies dominated the market and cooperated on electricity production and the planning of new plants in a joint-stock company, SEP, which was dissolved in 2001 (IEA 2009, 91). With liberalization came the unbundling of supply chain components into regulated (transmission and distribution networks) and non-regulated parts (generation and retail). Networks were deemed natural monopolies, while production and retail could be competitive. This would allow for efficiency improvements, lower costs for the consumer, and increased flexibility, though it would prove to involve an increasing number of actors and the management of their coordination via regulations. "Following market liberalisation, the four original generators continued to dominate the market, although there has been significant new entry and two of the four were acquired by foreign utilities. The retail market was fully liberalised on 1 July 2004, with all retail customers free to choose their own electricity supplier. At the same time, legal unbundling of supply and distribution network operations was instituted" (IEA 2009, 91).

[111] The tariffs calculated by network operators are subject to approval by the regulator. Moreover, "TenneT and distribution system operators are obliged to offer every connected party transport service" (IEA 2009, 96).

grid (maintaining voltage levels) to ensure continuous service, solving congestion and other transport restrictions, facilitating interconnection with neighbouring electricity systems in Belgium and Germany, conducting network maintenance to ensure maximum capacity availability, and regulating network access (IEA 2009, 91-92). In addition, "TenneT is also the majority owner (74.5%) of APX, the short-term trading exchange for gas and electricity" (IEA 2009, 92). Timetabling is very important to the execution of these network operation tasks. TenneT needs to be notified by electricity traders and suppliers regarding their "supply or demand 24 hours in advance for each period of 30 minutes" (Finger and Künneke 2007, 8). TenneT then investigates the technical feasibility of these contractual commitments to produce or deliver electricity between suppliers and customers in terms of available capacity and maintaining the balance between the electricity entering and exiting the network, and monitors transport to coordinate if need be. Here, redundant transport and back-up production capacity play an important role in assisting the TSO in accomplishing its tasks. In addition, TenneT assesses the actual amount of electricity supplied and demanded after delivery, since they might differ from the planned amounts due to unexpected outages or consumption patterns (Künneke et al. 2007, 8). It may bill all 'program responsibles', i.e. each party (usually supplier) that has one or more entry or exit points to the net, for the imbalance. Another major responsibility of TenneT involves infrastructure investment and grid planning. However, because grid planning requires coordination between TenneT, the DSOs, and other international TSOs, TenneTs investment decisions are "subject to *ex post* regulatory approval by the *Energiekamer* [while the Dutch] government is considering implementing *ex ante* approval for large projects in order to create stronger incentives for strengthening the network for the longer term" (IEA 2009, 100).[112]

In contrast to TSOs, DSOs "only have limited local tasks for the supply of electricity from the high voltage delivery point to the final customers" (Finger and Künneke 2007, 14-15). They primarily monitor and facilitate system performance by guaranteeing sufficient and reliable network capacity for service provision and compliance with regulatory standards. To coordinate the interconnections between the TSO and the various DSOs, a clear division of labor along the 'smart' transmission operator and the 'dumb' distribution operator has been set up in the Dutch netcode.[113] Ten regional distribution companies (including Stedin, Enexis, Cogas, Liander etc.), unbundled regulated monopoly firms owned by provinces and municipal governments, ensure the construction, maintenance, and operation of the

[112] "Under the Electricity Act, every other year TenneT must issue a grid plan, which describes any required additional transport capacity, as well as possible grid bottlenecks for the medium- to long-term period" (IEA 2009, 99).

[113] According to UCP (2010, 28-30), the "TSO network is considered intelligent, based on the SCADA (supervisory control and data acquisition) technology that is already implemented. Intelligence, in this context, concerns measurements in the network and either remote or autonomous control of network operations based on these measurements. However, the DSO network is essentially only a conductor for gas and electricity with as of yet very little control and measurement, and therefore with little intelligence."

bulk of the 259241 km electricity grid and are responsible for the connection of households and smaller customers to the below-110kV grid.[114]

In the Netherlands, electricity metering for small users is "the joint responsibility of the distribution network operators and the retailers" (UCP 2010, 28-30). In other words, it is a hybrid entity: "installation, metering asset-management and raw data collection occur in the regulated domain, while information management occurs in the commercial domain" (UCP 2010, 28-30). This created some complex data transfers, causing problems with the reconciliation of metered data, delays in the confirmation of capacity allocation, and long-term demand response (IEA 2009, 96).[115] The actual use of meter data is mostly integrated with retailers / suppliers and is only rarely a separate activity. As we saw above with the timetabling of TenneT, each retailer has the responsibility to provide, in a timely and accurate fashion, the amount of electricity entering and exiting the grid, and at which points this occurs, to the respective TSO or DSO. Retailers may also outsource their metering responsibilities to third parties if these are recognized by TenneT as metering companies. The tasks of such a company include the placing of meters, meter maintenance, and providing meter data.

Concerning the retail market, industry consumes almost 40% of electricity (2006), making it the largest share, while the residential sector coveres over 23%, and other sectors combined 35% (commercial, public service, agricultural, and fishing) of total final consumption of electricity (IEA 2009, 91). In 2009, electricity was supplied by 33 companies "with a licence to supply electricity to residential customers and small and medium-sized enterprises (SMEs)" (IEA 2009, 93). 80% of the market share rests in the hands of Essent, Nuon, and Eneco[116], all fully owned by provinces and local governments (IEA 2009, 94). Other noteworthy retail companies are Oxxio, a new entrant, and RWE. According to the IEA, the retail market is lacking competition as evidenced by the low rates of customer switching (between 0.5% and 1% per month (IEA 2009, 94 and 103).[117]

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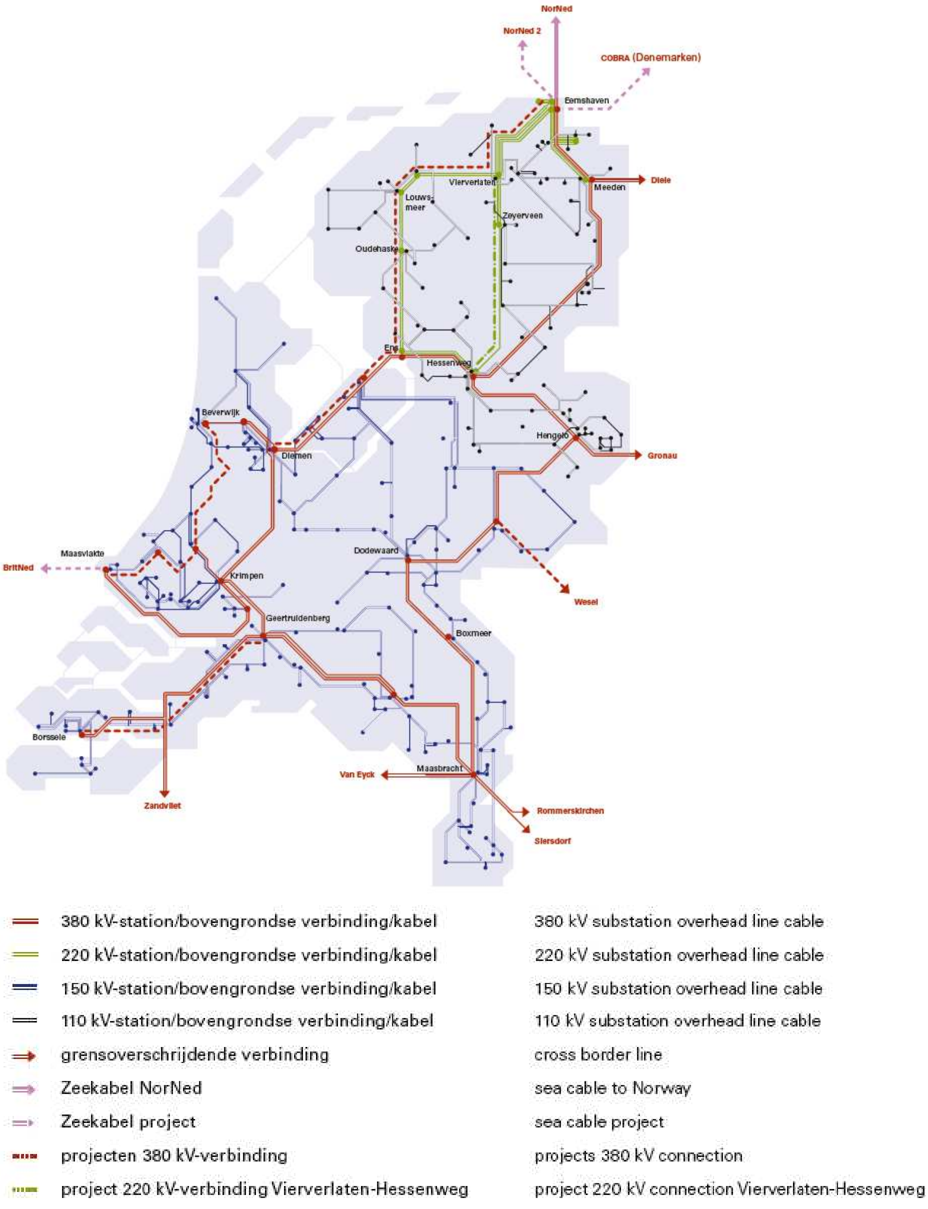
114 The Dutch government proposed a few years ago to enforce "ownership unbundling of distribution companies, in order to prevent the sale of distribution pipelines to private owners if the retail companies were to be privatised" (IEA 2009, 63). Distribution companies are currently challenging this proposal in court.

115 In response, the "industry and the regulator seem to agree that a new market model is needed, and implementation is now being discussed" (IEA 2009, 96).

116 The retail market shares of companies are: Nuon: 30 to 40%; Essent: 20 to 30%; Eneco: 20 to 30%; Oxxio (part of Centrica): up to 10%; RWE: up to 10%; Others: up to 10% (IEA 2009, 94).

117 Industrial users and households are free to choose their contract or pricing scheme. Yet real-time pricing is only available to industrial users while residential customers "are generally offered only day- and night-time pricing. […] However, this might change with the introduction of smart meters – meters capable of remotely measuring electricity consumption in real time, as well as transmitting real-time pricing information to customers" (IEA 2009, 94-95).

Figure 5.2 The Dutch electricity transmission grid



Source: Netbeheer Nederland and EnergieNed 2010, 34.

5.1.2 The Dutch Natural Gas Sector

Natural gas was discovered in the province of Groningen in the northeast of the Netherlands in 1959 by the Nederlandse Aardolie Maatschappij (NAM; Dutch Oil and Natural Gas Company), a joint-venture (50%-50%) of what would later become Shell and ExxonMobil (IEA 2009, 62). In 2008, natural gas reserves were estimated at 1390 billion cubic metres (bcm) - almost half of the originally 2600 billion cubic meters (bcm) large Groningen gas field -, of which just over a 1000 bcm are located in Groningen fields, 117 bcm in other onshore accumulations, and 198 bcm on the continental shelf (IEA 2009, 57). Roughly another 100 bcm of reserves exist, but they require sophisticated technology to be exploited economically. Moreover, these reserves are located in the Wadden Sea, an environmentally fragile and protected area. NAM is the country's largest natural gas producer and in charge of the main Groningen field, while several smaller producers (6 in 2009 (NNEN 2010, 14)) operate the remaining onshore Groningen fields and offshore North Sea fields (IEA 2009, 63). Two types of natural gas are produced domestically, "one with a low-range calorific value below 10.5 kWh/m^3 (L-gas), mainly from Groningen, and one with a high calorific value from 10.5 to 12.8 kWh/m^3 (H-gas), from smaller fields" (IEA 2009, 57).[118] Both high and low calorific gases require their own network. The total gas production in 2009 was 74659 million m3, an amount that has been steadily declining over the last few years.

After production, energy traders and suppliers buy natural gas and arrange for its transport to customers by contracting network capacity from network companies. Dutch wholesale trade is dominated by GasTerra, a company half state owned and half Shell and Exxon (25% each), with a share of nearly 60% in traded volumes. GasTerra both "sells domestically produced gas in the Netherlands" as well as being active on "the European gas market, and [having] import contracts with suppliers from Russia, Norway and Germany" (IEA 2009, 63).[119] An important feature in domestic production and supply is the so-called small fields policy established in 1973. It stipulates that the incumbent supplier, GasTerra, should "purchase gas from marginal wells at a price that ensures its competitiveness on the market" (IEA 2009, 60). Such a policy basically gives priority to gas production from small fields for providing the base-load, because it is technically more efficient to switch the Groningen field production on and off. As a result, the big Groningen field became a swing producer. In addition, the small fields policy "has had the positive effect of substantially increasing gas reserves over the last decades" (IEA 2009, 60). Internationally, the Dutch gas sector is of an important strategic position for

[118] "Nearly all domestic customers use blended low-calorific gas, while industry and power generators use mostly high-calorific gas. Some L-gas used by final consumers comes from H-gas, having been converted to L-gas in blending stations. L-gas is also exported through dedicated transmission pipelines to customers in Belgium, France and Germany" (IEA 2009, 61).

[119] "With the liberalization of the Dutch gas market, the length of GasTerra's supply contracts has shortened, to avoid the risk of allegations of use of market power when customers are bound for a long period" (IEA 2009, 64).

northwest Europe because of its interstate pipelines and export. In terms of gas flows, natural gas is produced from domestic reserves and imported from Norway, the UK, Russia, and Denmark, and exported to Germany, the UK, and Belgium and on to Italy, France, and Switzerland (IEA 2009, 68).[120] Regarding exports, the Netherlands has been a net exporter to Europe since the 1970s, even despite the currently declining domestic production.

Since July 2004, Gas Transport Services (GTS), a 100% affiliate of Gasunie, the Dutch state-owned infrastructure company that owns the transmission network (IEA 2009, 64)[121], is responsible for the operation, maintenance, and development of the national gas transmission transport network. This implies more precisely ensuring sufficient transport capacity, the balancing of the net, and the interconnection to other networks to meet the requirements of gas quality, supply security, and transport reliability (GTS website 26-01-2011). The prices that suppliers need to pay for the transport services of GTS are regulated and based on the entry-exit model. Basically, it is the responsibility of so-called shippers[122] to report the exact amount of gas entering and exiting at a certain time and point when contracting transport capacity at GTS. This is done for every hour 24 hours in advance. This balancing regime allows GTS to penalize shippers "whose gas shipments deviate from scheduled flows (as opposed to other countries that have put in place less punitive balancing regimes)" (IEA 2009, 64). GTS operates a transmission pipeline network of almost 11500 km in length, connecting "52 entry points (35 from Dutch gas fields and 17 from networks in neighbouring countries), 1100 delivery stations, 23 export stations and 9 compressor stations" (IEA 2009, 64). As Figure 5.4 nicely indicates, the high and low calorific gas is transported in separate networks. It connects the Groningen and North Sea natural gas production and the port of Rotterdam feeder stations with the regional distribution and foreign transmission networks. It also serves as a four-way gas conduit connecting domestic and foreign producers to domestic (about 7068000) and foreign customers, representing more and more a gas roundabout. This view is enhanced by the active gas trade at the Title Transfer Facility, the virtual wholesale marketplace facilitated by GTS and executed by APX Gas NL, a state-appointed gas exchange company. Here, natural gas may be bought and sold by gas trading

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120 "In 2006, the transmission system operator recorded 982 TWh (100 bcm) of gas entering the system, of which 23% was imports and 77% domestic production, and 972 TWh (99 bcm) exiting, of which 55% was for export and 45% for domestic consumption" (IEA 2009, 68).

121 According to the IEA (2009, 62), the Dutch natural gas industry developed in the 1960s following the discovery of natural gas in the north-east (Groningen). Industry organization (gas production and transport) was originally based on joint management between the State, Shell and Exxon. This 'Gasgebouw' was progressively restructured; in 2004 the gas market was "liberalised with supply and management of the gas networks legally separated" and in 2005 "the incumbent was split into an infrastructure company, retaining the historical name Gasunie, and a trading and supply venture, GasTerra."

122 For the network companies, the suppliers are so-called shippers from the moment transport capacity is contracted. Traders do not transport gas, i.e. contract capacity at GTS, or act like gas suppliers.

companies as it passes over the network.[123] This increases the economic liquidity and technical flexibility of the gas market.

Despite the central role of GTS in infrastructure operation, the bulk of the in total 138732 km of gas pipelines is operated by ten distribution companies, among them Stedin, Enexis, Cogas, Liander etc. (NNEN 2010, 5 and 18), owned by provinces and municipal governments. The DSOs operate the lower-pressure pipelines (up to 8 bar), whereas the TSO operate those above 8 bar. Though DSOs are often perceived as a simple local extension of the national grid because the flow of gas is unidirectional from the transmission to the distribution networks, it should not be forgotten that they in fact do most of the difficult maintenance and operating work due to the length and urban location of the networks they operate. The border of responsibilities lies at the so-called 'Gas Overslag Stations' (GOS) or Gas Transfer Stations, or the 'overdrachtspunt' (exchange point) to be precise. Whereas the housing and connection belong to the DSO, the operation of pipes and the metering inside are the tasks of the TSO. These issues are clearly stipulated in the netcode, which also sets gas quality and service standards and procedures for the Dutch gas infrastructure.

Regarding gas storage, there currently exist four sites in the Netherlands (Alkmaar, Maasvlakte, Grijpskerk, and Norg (Langelo)) while three more are planned (IEA 2009, 68). "Storage is largely under long-term contract by GasTerra" (IEA 2009, 68). Storage capacity is just over 5 bcm, which "is relatively small compared to the size of the market (around 10% of total demand)" (IEA 2009, 68). However, this situation is not alarming due to the possibility of using Groningen as a swing producer. Nevertheless, more storage capacity is required to allow for competition between an increasing amount of gas suppliers and to better secure supply for customers considering the yearly decreasing production levels.

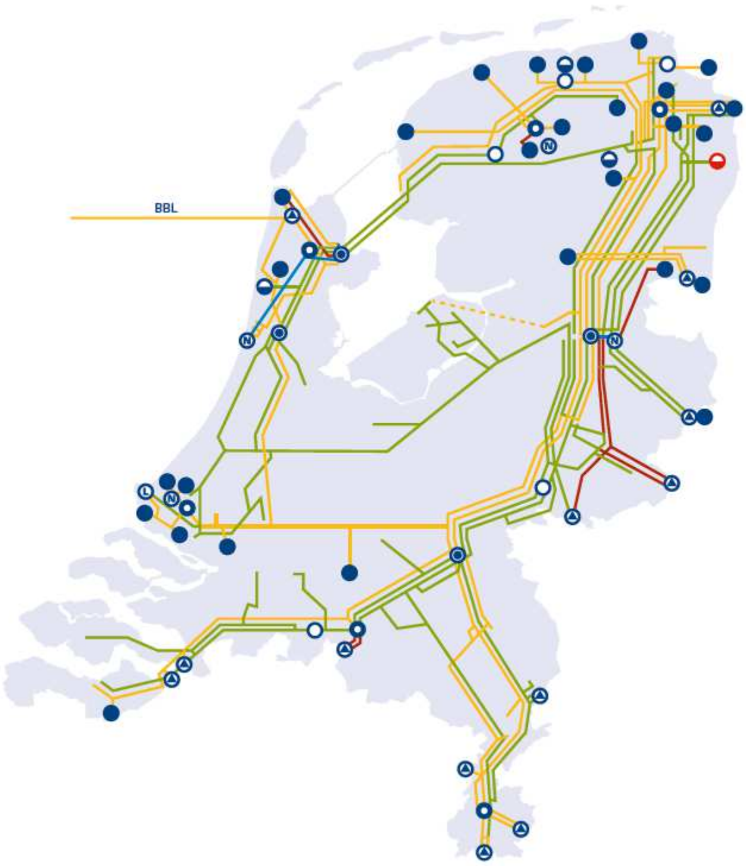
As with electricity, metering is a complex activity or entity in the Netherlands, with distribution network operators and retailers sharing the responsibility of gas metering for domestic (small) users. The DSOs own and operate the meters themselves and measure gas volumes during transport for billing and balancing reasons. The management of data and hiring of network capacity based on that data is the responsibility of retailers. Moreover, in principle, "the metering market is free in the Netherlands, and intermediaries have been created to gather and dispatch all metering data" (IEA 2009, 64). This creates a complex process of allocation, reconciliation, and confirmation of metered data (as with electricity). Generally, however, it are the retail/supply companies that buy gas from producers or traders, that reserve transport capacity from the national and local gas network operators, and that provide the metering data to the TSO.

Concerning retail, four gas supply companies, owned by provinces and municipal governments, dominate the retail market with a more than 85% share: Essent, Eneco, Nuon and Delta. In total, there were 33 licence holders in 2009 (NNEN 2010, 14) to supply gas "to residential customers and small and medium-sized enterprises (SMEs) with annual consumption under 170 000 m3" (IEA 2009, 63). Large-scale consumers, i.e. businesses and industries that use more than 170000

[123] "The geographical span of the Dutch TTF has a similar design to that of the UK's national balancing point (NBP). However, it is more complex" (IEA 2009, 68 and 70).

m3/year, are served by the transmission grid (GTS). "In the Netherlands there are about 18000 large users and 6.7 million small gas users, of which 6.5 million are households" (IEA 2009, 62). This is the "highest penetration rate of gas in OECD Europe" (IEA 2009, 61), exemplifying the maturity of the Dutch gas market. In 2007, the amount of total natural gas consumed was 46,4 bcm (IEA 2009, 61).

Figure 5.3 The Dutch natural gas transmission network



Source: Netbeheer Nederland and EnergieNed 2010, 35.

5.1.3 The Dutch Petrol Sector

Technically, when we look at the petrol infrastructure in the Netherlands, we are only focusing on the downstream part of a global oil infrastructure. Most sources can be found and much refining and transport takes place abroad or on the world's seas. Transmission pipelines or oil tankers represent the transmission part of the network through which most oil reaches the port of Rotterdam. From a Dutch perspective, the Netherlands is a major oil throughput country, i.e. a major importer of crude oil and exporter of refined oil products, with some minor domestic oil resources and generation and minor levels of importation for domestic use. The petroleum products sold in the Netherlands are almost all refined in the country. The Dutch total primary oil supply was 36.8 Mtoe in 2007 (IEA 2009, 72). Most of this supply comes from imports, with domestic production accounting for about 8% of this volume (3 Mtoe)[124], a percentage that has been declining over the last few years as domestic production "dropped to 2 million metric tonnes [in 2006] from 4.1 Mmt in 1990 and 2.3 Mmt in 2005" (IEA 2009, 61). Domestic reserves stand at an estimated total of 230 million barrels (Mb) on 1 January 2008, of which 148 Mb inland and 81 Mb on the continental shelf, according to the IEA (2009, 61).

Petrol is manufactured to exacting standards by refining crude oil in distillation towers "where constituents ('fractions') of heated crude oil are separated off at different boiling points [that are then] processed further into a wide range of products including [various car and plane fuels]" (OFTUK 1998, 15). The Dutch oil

124 The Mining Act of 2003 governs oil production in the Netherlands.

refineries are mostly located in the Port of Rotterdam area with a total capacity of 1.2 Mb per day, a utilization level of about 83% (IEA 2009, 74). The major players in the refinery sector are from large to small Shell, BP (Nerefco), ExxonMobil, Total, and Q8-KPE.[125] The refining locations are at Pernis, Europoort, Botlek, Vlissingen, and Europoort respectively. The refining sector is strongly integrated with the sizable Dutch petrochemical sector, whose major players include DSM, Sabic, Shell Chemie, Exxon Chemical and DOW Chemical (IEA 2009, 74), and which is similarly export oriented. After the crude oil is refined, the wholesale department of the refiner sells the petrol to retailers (fuel stations) or traders. Petrol wholesale prices are mostly based on global energy markets adjusted for transportation costs. For the Netherlands, as for northwest Europe, the bulk trade is often referred to as the 'Rotterdam Market' (OFTUK 1998, 45). This spot market operates by reporting the prices negotiated between oil companies and customers to journalists and agencies "who provide a daily report based on their contacts with the market participants: the two main reporting services are Platt's Energy Services and Petroleum Argus Ltd." (OFTUK 1998, 45).

The transportation of petrol as a refined oil product to fuel stations can be done via pipelines, road, rail, and ships. The Netherlands has about 418 km of pipelines for crude oil and 965 km for oil/petroleum products. Some oil is also transported via rail and river shipping to the European continent. Concerning the domestic use of petrol as a motor fuel, however, the petrol output of refineries is generally distributed via tanker trucks to retail sites in the vicinity by the wholesale department of the refiner. Next to selling and delivering petrol directly to fuel stations, the wholesale department of refiners may also supply other refiners or non-refining wholesalers. Supermarkets do not play a role in the Netherlands. These non-refining wholesalers are in essence either traders or dependent and independent distribution companies. These distribution companies may actually sell the petrol back to the refiners' own wholesale departments (Hoegen-Dijkhof ????, 3). Alternatively, retailers may play the role of distributors themselves if they own tanker trucks. If not, they may hire distribution companies to deliver the petrol to them. Tanker trucks are very flexible in use; not only can they carry various petroleum-based fuels such as petrol and diesel, but they also pose few technical barriers to entry, unlike pipeline systems. It is thus relatively easy for both refiners and non-refining wholesalers to enter the distribution business. However, "non-refining wholesalers obtain most of their petrol supplies from refiners [giving the latter a certain leverage. Not surprisingly,] the extent to which refiners supply their downstream competitors varies" (OFTUK 1998, 27).

Alternatively, petrol is transported from distribution terminals to filling stations. Such terminals are used for the blending and storing of a variety of fuels including petrol (and may operate largely automated). Put simply, whereas overseas crude oil goes into the refineries, overseas refined oil products arrive in such

[125] According to wikipedia (2011), these are the refineries in the Netherlands and their production: Shell 416,000 billion barrels per day (bbl/d), BP 400,000 bbl/d, ExxonMobil 195,000 bbl/d, Total 158,000 bbl/d, and Q8-KPE 80,000 bbl/d. (see http://en.wikipedia.org/wiki/List_of_oil_refineries#Netherlands). Data is ultimately derived from The Oil and Gas Journal which was inaccessible to us at this point.

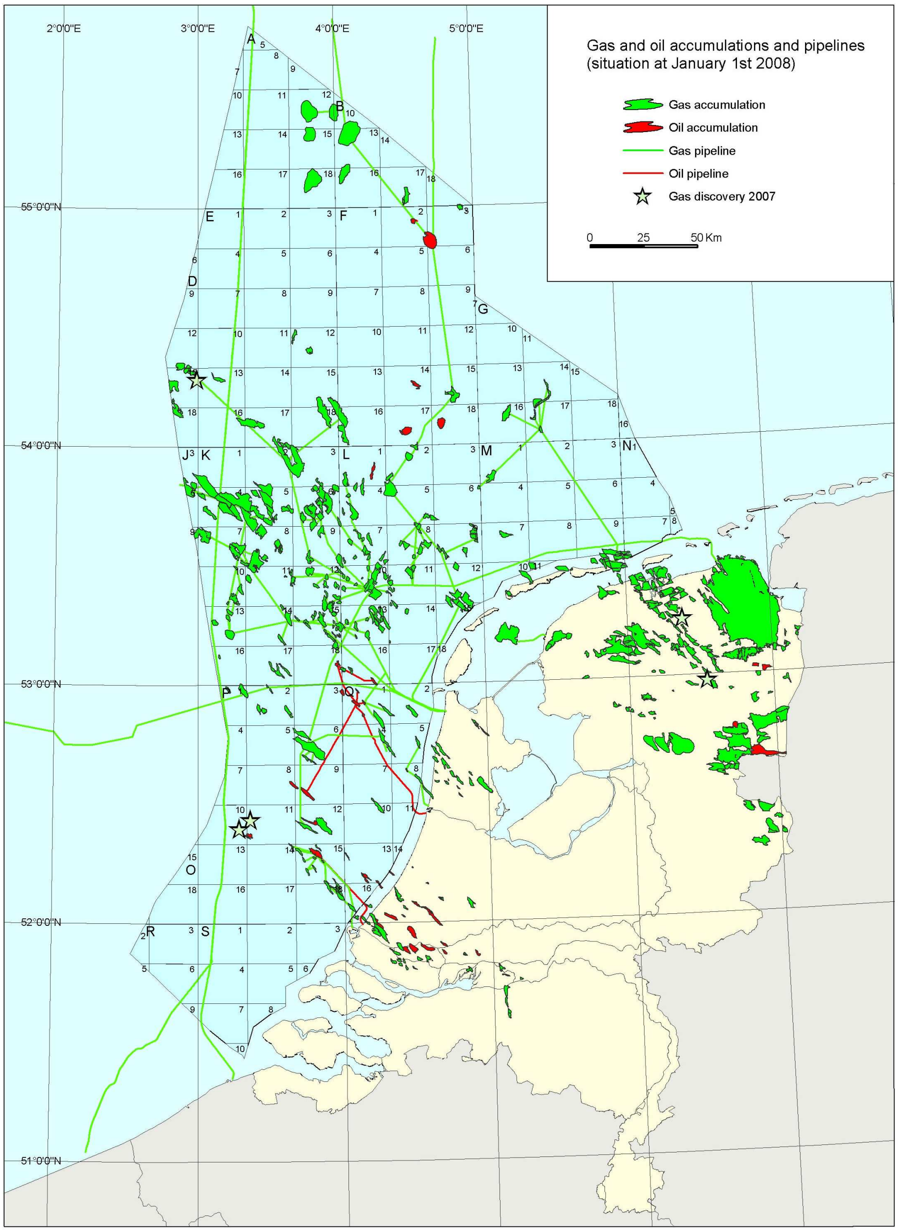
terminals. They are then either transported further into Europe by ship or throughout the Netherlands by truck (BP website, 1-11-2011). To compare, the BP refinery at Pernis (Europoort region) has a truck refuel station capacity of about 125 trucks per day, whereas BP's Amsterdam Terminal (BAT) has a capacity of 250 to 300 trucks a day making it the hub for supplying petrol to the northwest of the Netherlands. Of course, petrol may also be transported from refineries in the Netherlands to distribution terminals in the Netherlands. Refineries and terminals are frequently part of the same oil major (Shell, BP, etc.). The distribution of petrol from refineries or terminals to fuel stations often involves the use of more regional storage depots. In the Netherlands, there are 21 such oil and petrol depots. Some locations are Amsterdam, Arnhem, Groningen, Zwolle, Hengelo, Wageningen, Geertruidenberg, Roermond, Vlissingen, and Utrecht (BP website, 1-11-2011). These depots may be part of an integrated oil company that ensures refinement, sales, distribution, storage, and retail, but may also be owned by independent storage providers. An example of the former and latter would be BP or Shell and VOPAC respectively. A final important feature of petrol distribution are so-called exchange agreements or swaps between refiners. Swaps "allow for one company to provide the other with a particular quantity and quality of product from a refinery or terminal in one location, and to collect a comparable quantity and quality of product from the other company at another location" (OFTUK 1998, 26-27). Any imbalances that may occur are generally adjusted in future swaps. This way, refiners may supply "customers and retail networks in locations distant from their own refineries [allowing them to] maximize the geographic scope of their retail networks whilst minimizing transport and refining costs" (OFTUK 1998, 26-27). In the Netherlands, for example, the BAT allows Shell and others to refuel their trucks.

In terms of consumption, the largest share of the Dutch total primary oil supply went to the transportation sector (just under 50%), followed by industry (just under 33%), both for energy production and manufacturing (IEA 2009, 72). Concerning the transportation sector, there are about 3750 retail fuel stations in the Netherlands, of which about 2300 sell LPG (IEA 2009, 74). They fuel about 10,5 million vehicles; 7.7 million of them are cars (CBS statline, 1-11-2011). The fuel stations also act as meterers of petrol consumption. The Dutch petrol retail market is made up of integrated oil companies (uniting refining, wholesale, distribution, storage, and retail), branded dependent retailers, and independent retailers. Regarding the ownership and operation of fuel stations, three types can be distinguished (NMa, 2001): a) those owned and operated by oil companies; b) those owned and operated by an independent proprietor; and c) those owned by oil companies and operated by independent proprietors (Bettendorf et al. 2003, 672). In option a, the oil companies sell their gasoline "through branded filling stations" (Bettendorf et al. 2003, 672). In both options b and c, the filling stations often have "exclusive and often long-lasting supply contracts with one of the major oil companies [who] recommend retail prices to their filling stations [while] standard margins for filling stations operators are agreed beforehand" (Bettendorf et al. 2003, 672). The oil companies are the dominant players. In terms of volume of gasoline sold (not to be confused with the amount of filling stations owned), the major oil companies combined account for 84%. Shell is market leader with a 30% market share, followed by BP (19%), Exxon and Texaco (both 11%), Total/Final/Elf (10%), and Q8 (3%), while the total of all independents combined ranks at 16% (Bettendorf et al. 2003, 672-673). In terms of operation, 24% of retail filling stations are operated by independents, 18% by both Shell and BP, 14% by Texaco, 13% by Total/Final/Elf, 9% by Exxon, and 4% by Q8. Hence, the volumes of gasoline sold and filling stations operated are roughly equal, except for Shell and the independents, the so-called 'white pumps'. While Shell has a relatively large volume sold per filling station, independents show a relatively low volume per station. This seems to be because "branded filling stations, unlike the non-branded ones, are mostly located at the prime locations like motorways" (EC 1999; Bettendorf et al. 2003, 673). There seems to be little brand loyalty in the retail market due to the fact that petrol is a homogenous product, i.e. there is "little or no trade off between price and quality" (OFTUK 1998, 17), and is considered a necessary commodity. In turn, buying behaviour is a matter of convenience and the retail market is rather price-sensitive.[126] "Entry into the retailing market is currently unattractive given the low margins available on fuel sales and the costs of complying with environmental legislation" (OFTUK 1998, 21-22).[127]

[126] It is important to note here that petrol and diesel are not "demand side substitutes since cars designed to run on diesel cannot take petrol and vice versa. [Of course, increasing in price in gasoline may still affect long-term car sales and so indirectly affect the diesel market, however weak this may be; it is therefore hardly the same market] However, on the supply side, wholesalers and retailers can switch between supplying diesel and petrol since the equipment required for each product is the same" (OFTUK 1998, 19). For refining, finally, petrol and diesel may again be separate.

[127] Complaints about high gasoline prices have a long history in the Netherlands. "To the public, it seems that the oil companies adjust the retail gasoline price more quickly to cost increases than to cost decreases" (Bettendorf et al. 2003, 670). The NMa concluded in its 2001 report that "competition is considerably restricted in the Netherlands. Its investigation reports that the large oil companies (Shell, BP, Exxon, Texaco and Total/Final/Elf) keep the price of motor fuels artificially high" (Bettendorf et al. 2003, 674). Moreover, it seemed that online publications of Shell's recommended prices are usually followed by other companies, except at the Dutch border to Germany and Belgium (EZ 2002; Bettendorf et al. 2003, 672). There also have been several parliamentary enquiries on the relatively high petrol prices as compared to the EU in 1999 and 2008. Finally, the European Commission mentioned as early as 1999 "that the wholesale and retail margins appear to be inexplicably higher in the Netherlands than in the other European countries [and that the] resulting high pump prices cannot be attributed to higher taxes or costs[, hence hinting at the fact that] the higher price environment in the Netherlands shows a deficit of competition" (Bettendorf et al. 2003, 673). The restrictive planning and permission policy of the Dutch government also does not help to improve the prospects for stronger competition. "Partly as a result of this policy, the number of filling stations in the Netherlands has been strongly reduced over the last 10 years: from 6600 in 1990 to 3900 in the year 2000" (Bettendorf et al. 2003, 673). Nevertheless, these concerns about insufficient competition in petrol retail have urged the Dutch government to implement measures "such as auctioning filling stations on motorways in order to encourage new entrants and to increase competition in the retail fuel market" (IEA 2009, 74).

Figure 5.4 Dutch oil and gas fields



Source: TNO 2007, 12.

5.2 Applying the Framework to Dutch Energy Infrastructures

Let us now explore the framework on the electricity, natural gas, and petrol sectors. This will allow us to learn from its application in order to refine the framework before using it on future energy systems. This will be done at the hand of the four steps discussed earlier; a) identifying the critical technical functions and their required control mechanisms; b) allocating which entities are involved in the facilitation of the technical functions; c) assessing control mechanisms in terms of their coordination requirements; and d) translating the outcomes of step two and three into one overarching organizational structure. One important matter to keep in mind while reading sections 5.2.1 to 5.2.3 is that for the framework application we may only take the technological characteristics of these infrastructures as inputs. We thus purposefully ignore the organizational (and economic and institutional) knowledge that abounds since that should be the output. For example, we have to discuss the actors mentioned above as unknown supply chain entities that have their particular roles and responsibilities in infrastructure operation (see Table 5.1 below). Afterwards, section 5.2.4 compares the results of the framework with the current practical organization of the sectors in light of reliability performance.

Table 5.1 Main infrastructure entities per sector

	Electricity	Gas	Petrol
Sources	Natural gas, coal, nuclear, renewables	Natural Gas	Crude oil
Production / refinement	Electrabel, Essent, Nuon, E.ON Benelux, and Delta	NAM	Shell, BP, Exxon-Mobil, Q8-KPE, and Total/Final/Elf
Trade	Mainly APX Facilitated by TenneT	GasTerra Facilitated by GTS	Rotterdam Market All parties involved
Transmission	TenneT	GTS	-
Storage	-	GasTerra, GasUnie, Eneco, etc.	Shell, BP, Vopac, etc. (21 in total in 2009)
Distribution	Stedin, Enexis, Cogas, Liander, etc.	Stedin, Enexis, Cogas, Liander, etc.	Oil majors, retailers, (in)dependent distribution companies
Metering	See retail plus some metering companies	See retail plus some metering companies	See retail
Retail	Essent, Nuon, Eneco, Oxxio, and RWE	Essent, Eneco, Nuon, and Delta	Fuel Stations (Shell, BP, dependents, and independents)
Consumer	Households and industry	Households and industry	Automobiles and other transport applications
Regulator	Office of Energy Regulation	Office of Energy Regulation	Netherlands Competition Authority

5.2.1 What Organizational Structure for Electricity?

5.2.1.1 Critical Technical Functions and Control Mechanisms

Interoperability concerns the complementarity of system components (between energy sources or carriers and network specifics, energy characteristics and applications requirements, and regulatory conditions for access) and the planning for the incorporation of future components. For electricity, all these issues are relevant. For example, voltage margins and alternate current amplitudes need to be agreed upon and codified, a choice between 110 or 220 volt plugs and applications needs to be made, generation and transportation specification need to be set, and the electricity generated needs to meet the voltage levels of the intended national or local grid. All such issues require "a close standardization of technical processes and requirements with respect to the quality of electricity that is delivered throughout the system" (Finger and Künneke 2007, 8). In addition, it is likely that new renewable sources will need to be integrated into the existing electricity grid. Whether large-scale wind parks or local solar panels, they all use electricity as an energy carrier. The appropriate control mechanism appears to be the development of and compliance with / enforcement of norms and standards in order to ensure that the national and regional electricity networks function as one.

Interconnection encompasses the facilitation of existing local, regional, national, and international network linkages and transmission planning. Both issues apply. For example, the physical links among various low-, medium-, and high-voltage grids need to be ensured. This can be done with the help of additional technical measures such as switching stations, which aid in the exchange of electricity between systems, but the real matter to resolve is the division of labor regarding which network company should own and operate what voltage levels. Clear agreements in this regard are vital. In all, someone needs to monitor and facilitate interconnection. In addition, plans for future network extensions, like decentral domestic solar pv or centralized North Sea wind power, need to be made to incorporate future ambitions for a more sustainable energy system.

Capacity management concerns the operational real-time balancing and the tactical and strategic management. Let us discuss these three in turn. Operational balancing involves the continuous operation of the network in terms of the regulation of energy flows and content, disturbance response, and automatic protection to minimize equipment damage and service interruption. For electricity, all of these tasks need to be ensured. "Because one cannot store electricity [on a significant scale financially attractive or technically efficient], balancing an uncontrollable demand for electricity, available production possibilities, and physical network capacity is a very challenging task" (Finger and Künneke 2007, 8).[128] In addition, the physical delivery of electricity cannot be controlled or directed because electrical currents follow the

[128] "Usually there is no demand side management involved in the operation of electricity systems" (Finger and Künneke 2007, 8).

differences of resistance within the network according to the physical law of Kirchhoff. Finally, failures and outages of lines need to be repaired on the spot because electricity flows with the speed of light through the net and because network inputs and outputs need to be in equilibrium at all times in order to avoid imbalances that may lead to blackouts. A central control room that operates the entire network is required to manage these flows through the national and various regional networks in order to prevent over- and under- loads from occurring. Tactical capacity management concerns unit commitment and maintenance scheduling. These are both very important issues for electricity. First, electricity generation operates optimally at certain production levels. Shutting down and starting up generators may involve high costs depending upon the energy source used. Moreover, network capacity needs to be committed a day in advance for every 30 minutes. Contracting between producers, suppliers, traders, and the network companies involved takes a central role in the facilitation of energy transport. Second, regular network maintenance work must be executed and incorporated into operation schedules. Front and back offices that schedule and execute contracts are required to ensure tactical management. Strategic capacity management involves the long-term generation and fuel planning. Important issues for electricity in this respect are the building of new power plants (coal, gas, nuclear) and to introduce renewable electricity. Where to build new coal-fired power plants with CCS or centralized wind farms? How to connect them to the grid, building new capacity if necessary? How to facilitate decentralized solar energy into the existing electricity grid? Some planning among network companies and energy producers is required in this regard to be prepared for the future.

System management concerns the management of the overall system in terms of aligning energy supply to the quantity demanded and quality of service. For electricity, load management is vital; this entails both the provision of sufficient back-up capacity in case of unexpected demand fluctuations and keeping an eye on voltage levels and frequency. Because one cannot store electricity efficiently, demand fluctuations need to be compensated for by sufficient flexible generating capacity and supported by redundancy. Whereas flexible generating capacity may quickly and responsively increase and decrease production at little cost due to low efficiency losses during start-up and shut down (loading), redundant network parts may be used when demand rises steeply and cannot be served by the standard gird. Electricity benefits from being an energy carrier and not a source. As it can be made from many sources, switching from one to another in case of supply security concerns in one particular source (gas, coal) helps to have a secure generating capacity. Electricity also benefits from its maturity. Consumption patterns and seasonal fluctuations are well known. The quality of service relates to the trade-off between availability, affordability, reliability and sustainability of the electricity produced and transported. Such a decision is not part of the technical process as such, but more a matter of political choice that may affect future technical processes. In this sense, the shift to the use of renewable energy sources seems most pressing, although as of 2010 they are not yet a matter of great concern, as we will see in the next chapter. For now, renewable energy is mostly small-scale and does not affect the electricity network as a whole.

5.2.1.2 Allocating Technical Functions

Let us now see which supply chain entities are involved in what critical technical functions. The overview of the electricity sector in section 5.1.1 shows that there are a small variety of sources with which to generate electricity, there is a core group of a few electricity producers, and that there are many traders. Regarding the network, TenneT is the single TSO, there is no notable entity storage, there are a few DSOs, and metering may be a separate entity but is mostly integrated with retailers (and DSOs). Concerning the application end of the supply chain, many retailers exist albeit that the entity is dominated by a few, that there are millions of household and thousands of industrial consumers, and that there is one regulator (the Office of Energy Regulation).

Regarding interoperability, the establishment of norms and standards is mostly a regulatory matter. While it involves consultation among producers, TSOs and DSOs, in the end electricity generation and network specifications need to be codified by a regulator. Complying with standards on a daily basis is the responsibility of network companies, while producers are directly involved through electricity production. Retailers should not be included because they do not manage the metering assets. The regulator may or may not be directly involved in daily operations depending on the need for regulatory oversight to ensure compliance.

Interconnection planning and facilitation is a typical responsibility for network companies. Considering the dominant position of the TSO in Dutch electricity network operations due to its role as connector between central power plants and the local networks, its key role in grid planning, and its relation with other foreign TSOs, it may be considered the leading entity. The DSOs in turn are strongly involved in daily operations, but follow the lead of the TSO.

Capacity management involves almost all entities. While the core responsibilities lie with the TSO and to a lesser degree regional network companies, producers are involved as electricity suppliers, retailers as the program responsibles hiring network capacity to deliver electricity to customers, metering may be involved through providing demand data, and traders as intermediaries between producers and network companies that enhance overall efficiency. Looking closer, we see that electricity transport and quality, disturbance response, and automatic protection concerns of operational balancing are an exclusive task of network companies, first and foremost the TSO in a leading role, with DSOs strongly involved as key responsible entities. The scheduling of capacity of tactical management similarly involves first and foremost network companies, whereas producers adjust electricity generation in direct coordination with the TSO, retailers or shippers deal with the TSO and DSOs regarding scheduling, metering firms may play a supportive role in providing demand data, and traders may help balance short term imbalances by acquiring electricity. Regulators, finally, may influence this process by setting network tariffs. The generation and fuel planning of strategic management also primarily involves the TSO and DSOs, and secondarily the producers and regulator. While producers make investment decisions on which fuels to generate in the future, TSOs need to consider the connection of these new power plants, and the regulator needs to approve such plans.

Finally, system management, i.e. ensuring the quantity and quality of the electricity delivered for the overall system, seems to be operationally dependent on producers (quantity and quality of electricity generated) and network companies (ensuring no intermittency), with retailers (for establishing the demand of consumers) being directly linked to them. Traders and metering companies are intermediaries that may support the facilitation of the infrastructure service, but which are not necessarily involved, while consumers affect operations (via their consumption patterns and preferences). The sources for electricity production are also important in order for production to take place. Finally, regulators set important ramifications such as the rule that everybody that wants access should have access (it is compulsory for Dutch network companies to connect any customer who wishes to be connected). The result is summarized in Table 5.2.

Table 5.2 Contribution of entities to electricity operations per technical function

Entities	Amount	Inter-operability	Inter-connection	Capacity Management	System Management
Sources	Few	--	--	--	-/+
Production	Few	+/-	--	+	+
Trade	Many	--	--	-/+	-/+
Transmission	One	+	++	++	+
Storage	Irrelevant	--	--	--	--
Distribution	Few	+	+	+	+
Metering	Many	--	--	-/+	-/+
Retail	Many	--	--	+/-	+/-
Consumption	Millions	--	--	--	-
Regulation	One	-/+ or +	--	-/+	-/+

Legend: 6 degrees of involvement are distinguished from least to most:

- -- No involvement.
- \- Indirect involvement (entity affects operation or planning).
- -/+ Supportive involvement (set ramifications, data providers, oversight).
- +/- Weak direct involvement in daily operations (entities involved in operations).
- \+ Strong direct involvement (key operational responsibilities).
- ++ Leading involvement (central coordinating entity, system operator).

5.2.1.3 Assessing Coordination Requirements

So what are the coordination requirements of the critical technical functions? We identified the development and compliance with codes and standards as the control mechanisms that ensure interoperability. In terms of scope of control and speed of adjustment, it seems straightforward that the creation of codes and standards is a long-term system level issue because it requires many rounds of consultations among a variety of entities. Standardization is a process rather than a point in time. Actually complying with standards is less obvious however. While it definitely involves an effort by individual entities at the component level in the very short term due to the speed with which electricity flows pass through the network, it is unclear from a technical perspective to what extent it also requires a more systemic regulatory effort, i.e. enforcement. On the one hand, compliance to standards might need to be enforced by an operator and supervised by a regulator. On the other hand, compliance might be in the self-interest of the infrastructure entities, for otherwise they compromise their objectives and/or cannot fulfill their operational responsibilities. If so, voluntary adjustment might make enforcement unnecessary. Decisive in this regard is likely to be the maturity of the system as a whole. As we saw in chapter 3, emerging systems often still have to configure their exact technical characteristics whereas components in mature systems are finely tuned to one another. Considering that electricity falls into the latter category, compliance seems to have become a matter of self-interest to entities operating or utilizing the infrastructure. This would lead to a mode of organization for interoperability of 'directive planning' and 'upholding general framework conditions'. Focusing on facilitation over planning in the establishment of the overall criticality of interoperability, the accompanying coordination requirement would match that of medium criticality (common operation based on agreement between autonomous entities).

Interconnection involves the planning of new network segments and the monitoring and facilitation of existing linkages. Transmission planning is a long-term system level issue although it eventually may involve the development of new sections in the medium term. Daily facilitation of interconnection takes place at the system level, mostly between the national and regional level, in the immediate term. Considering the speed with which electricity moves through the grid and that electricity can hardly be stored, or no buffer exists other than switching stations, local network connections need to be considered at the system level because failures in local parts of the grid may easily affect national operations. This would lead to a mode of organization for interconnectivity of 'directive planning' and 'authorative supervision'. This entails coordination requirements of the highest criticality (necessitating a coordinating center that dictates and supervises).

Capacity management is arguably the most critical technical function for electricity, due to the physical nature of electricity flows and their lack of adequate storage possibilities, and requires tight coordination to ensure system integrity. Operational balancing of electricity flows takes place instantaneously and continuously (in the immediate term) and involves the entire grid (transmission and distribution). Due to the lack of storage, flows need to be redirected immediately if needed. As Künneke et al. (2008, 20) put it: "Since system wide critical transactions are involved and technical balancing needs to be assured on the spot, only a centralistic and prescriptive approach of organization can meet these requirements. This can be imagined as the most critical transaction." This would lead to a mode of organization of 'authorative supervision'. In addition, the scheduling and monitoring activities of capacity utilization (tactical management) takes place in the short term (a day in advance) and for the entire electricity grid. This involves 'compulsory monitoring and enforced adjustment'. Strategic management obviously involves a longer time horizon, but still remains at the system level: directive planning followed by a controlled allocation mechanism for eventual development. Focusing on daily operations over planning, capacity management requires central control of the network by a transmission operator. In terms of criticality, this involves the highest possible, the need for a central coordinating center that dictates and supervises.

System management is an equally challenging task. Because electricity cannot be stored efficiently and sufficiently, demand fluctuations must to be balanced by supply. This necessitates a close connection between electricity producers and network operators. Monitoring of electricity balance needs to be done continuously and action needs to be undertaken immediately if electricity demand deviates from the expected amounts reported the day before. Being almost by definition a systemic technical function, the corresponding mode of organization is 'compulsory monitoring and enforced adjustment'. In terms of criticality, this would be of the highest criticality, again requiring a central coordinating center that dictates and supervises.

Overall, it seems that capacity, system management, and interconnectivity require a high degree of centralized control whereas interoperability can be organized in a more decentralized fashion. The broader environment seems to emphasize the need for central coordination even further. The Dutch electricity network can be considered complex with a few entry but millions of exit points. At the same time there is little room for flexibility at lower levels to deal with complexity due to the tightly coupled or highly interdependent nature of the grid. Small local failures may have immediate national consequences. Only the intensity seems countered by sufficient redundancy, creating some leeway in dealing with network traffic fluctuations. In general, therefore, control mechanisms are employed in a non-forgiving environment. The results are captured in Table 5.3.

Table 5.3 Coordination requirements of technical functions for electricity

	Interoperability	Interconnection	Capacity management	System management
Coordination requirements	-/+	++	++	++

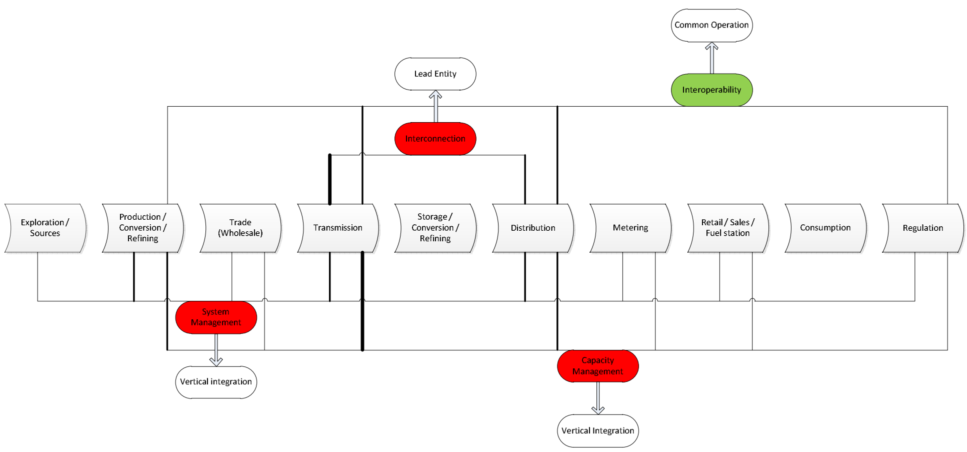
Legend: 6 degrees of criticality / central coordination requirements can be distinguished:

- -	Not critical; autonomous entities act without need for coordination.
-	Low criticality; autonomous entities that voluntarily adjust operation to a common rule/goal.
-/+	Medium criticality; common operation based on agreement between autonomous entities.
+/-	High criticality; continuous coordination between key entities.
+	Very high criticality; central coordinating center that monitors and responds.
++	Most critical; central coordinating center that dictates and supervises.

5.2.1.4 Towards an Organizational Structure for Electricity

Combining steps 2 and 3 for interoperability yields a combination of medium criticality and a central role for the TSO and DSOs, with producers involved to a lesser extent. Regulators play a marginal role in daily operations, instead setting standards in the long run. This leads to an organizational structure of 'common operation'. Interconnection involves the cooperation between the TSO and DSOs and the highest levels of criticality. The monitoring of interconnectors and the short response time involved urge for the structure of a 'lead entity' in which the TSO dominates. The TSO and DSOs also play key roles in capacity management, while producers and retailers (and metering companies) are closely related to grid balancing and unit commitment operations. Combined with the most critical situation that operational balancing and tactical management may face, the appropriate organizational structure is 'vertically integration'. Though a lead entity structure with the TSO as leader also seems suitable, the need for tight and immediate coordination between producers and the TSO calls for their integration in terms of system operations. System management contains very high criticality combined with many entities that are roughly equally involved (TSO, DSOs, metering, retail, and production). This suggests organizational requirements of 'vertical integration' to match supply and demand. Figure 5.5 shows the result.

Figure 5.5 Towards an organizational structure for electricity



Legend: No and indirect involvement = no line
Supportive and weak direct involvement = normal line
Strong direct involvement = bold line
Leading involvement = fat line

Not critical = white
Low criticality = blue
Medium criticality = green
High criticality = yellow
Very high criticality = orange
Most critical = red

So what does this imply for the overall organizational structure? The most critical task is capacity management, followed closely by system management and interconnection. The key entities responsible for these functions are first and foremost the transmission system operator and distribution companies, followed by producers and retailers (and meterers). According to the logic that the entities dealing with those critical technical functions that require a centralized mode of organization should become the lead entities in the overall infrastructure (and those that deal with less critical technical functions may be vertically integrated with it or separated from it, or even be completely autonomous), it seems that the TSO and DSO entities should be at the heart of the organizational structure. This perspective is enhanced by the large-scale centralized nature of production and the unidirectional nature of electricity flows from the transmission to the distribution grids. While this may suggest a structure in which the TSO is the lead entity, the immediate nature of electricity flows and the complex and tightly coupled grid, make electricity generation and retail (and metering) so strongly and directly related to the maintenance of network balance that vertical integration seems required to coordinate operations successfully. In the end, the natural monopolistic features and technical economics of vertical integration are so strong and the benefits from system complementarities (economics of system) so great that a single monopolist under regulation is the most efficient option in terms of reliability. To conclude, in terms of the organizational structures identified in chapter 2, the required organizational structure is that of 'vertical integration'.

5.2.2 What Organizational Structure for Natural Gas?

5.2.2.1 Critical Technical Functions and Control Mechanisms

Interoperability concerns the complementarity between system components. For gas many issues apply. Whether it are the molecular characteristics and pipeline specifics of natural gas, vaporisation for safe use, or gas composition standards for feed-in, all require a high degree of standardization on gas quality and pipeline technology and agreements on codes of conduct to ensure cross-network operations. For the Netherlands, this counts double as gas quality needs to be checked for the separated pipelines for high- and low- calorific gas. Moreover, possibilities of adding biogas to the natural gas network might require new, less stringent, standards in order to ensure the economic and technical feasibility of that venture. They might also require new gas quality control schemes regarding where to check, at the feed-in point or at a more central node. Hence, the development and enforcement of norms and standards in order to ensure system functioning seems to be a necessary control mechanism again.

Interconnection encompasses facilitating existing network linkages and transmission planning. Both issues are relevant for gas. First, the physical links among various low-, medium-, and high- pressure pipeline networks needs to be assured by so-called 'Gas Overslag Stations' (GOS) or gas transfer facilities. As with electricity, responsibilities need to be clearly stipulated; which network company should own and operate what pressure levels? Unlike electricity, however, natural gas' storage possibilities allow for a buffer at these nodes in case of emergencies. Second, gas networks are still steadily expanding each year both at the local level, adding new users to the system, and at the national/international level where a North-West European network is slowly but surely being established. Of course, future planning with regard to the energy transition is also taking place. For example, where to feed-in biogas? The operation of network connections and planning for extensions needs to be constantly facilitated and monitored.

Capacity management concerns the operational real-time balancing and the tactical and strategic management. For gas, these are all highly relevant. The main challenge for operational balancing lies in the continuous monitoring and supervision of gas pressures and volumes in pipelines so that supply matches demand. However, in contrast to electricity, natural gas flows can be controlled through pressurization, gas can be stored, and the Groningen gas field provides swing production. Altogether, these open up possibilities for control that may ease reliable operation. Nevertheless, failures and outages need to be repaired immediately to avoid imbalances that may lead to service interruptions. Another main challenge is the monitoring of gas compounds. Gas contents may vary considerably per producer, a challenge aggravated by the maturing wholesale market which invites more foreign gas flows. In the end, central control of the network is required to manage the flows through the national and various regional networks and prevent failures. Tactical capacity management concerns are also highly relevant matters for gas networks. Natural gas enters the Dutch transmission grid from a variety of angles (domestic production, Norwegian, British, Russian gas imports and exports to Germany and Belgium etc.), creating a complexity of flows: from the Netherlands to the Netherlands, from the Netherlands to foreign countries, from foreign countries to the Netherlands, and from foreign countries to foreign countries through the Netherlands. Committing network capacity a day in advance for each hour is an important necessity. So contracting between producers, retailers (and meterers), traders, and network companies takes again a central role in the facilitation of energy transport. Unlike electricity, however, switching generation facilities on and off, though inefficient it may be, does not affect network balance as immediately because there is more space for later adjustments due to storage possibilities. Of course, regular network maintenance must also be incorporated into operation schedules. In sum, front and back offices for contracting and contract execution are required. Strategic capacity management of gas is mostly challenged by the finite gas resources. Though exploration may uncover new deposits, eventually, natural gas will have to be replaced by other energy sources. Interesting questions with regard to generation planning include: what should replace natural gas (electricity, biogas?); what role can natural gas or its network play in a transition towards renewable energy sources? Natural gas is a comparatively clean fossil fuel, after all. Some planning among network companies and energy producers is required in this regard to be prepared for the future.

System management concerns the management of the overall system in terms of aligning energy supply to the quantity demanded and quality of service. To start with, balancing demand and supply at home is fairly easy due to domestic production, natural gas' storage possibilities, and the Dutch role as an energy hub. Moreover, the use of the Groningen gas field as a swing producer helps to build a defense against demand fluctuations. Hence sufficient back-up capacity is present. But beyond that, there might be challenges with supply security from gas exporting countries over which there is no control. Moreover, there are export contracts that need to be maintained at any given time. The Dutch cannot simply use other nations' gas when they need it. Regarding the quality of service, two issues dominate. First, how to ensure affordability in times of increasing scarcity (decreasing availability)? Second, how to make a transition to sustainable energy technologies while not jeopardizing reliability. As with electricity, the latter involves mostly small-scale renewables at the present stage and does not affect the gas network as a whole. Yet some planning in this regard needs to be done.

5.2.2.2 Allocating Technical Functions

Let us again allocate the critical technical functions to the supply chain components. The overview of section 5.1.2 has shown for the generation part of the gas infrastructure that there is no entity sources, one domestic producer (NAM), and that trade is dominated by a single actor (GasTerra). Regarding the network, there is one TSO (GTS), a few companies to represent storage, a few DSOs, while metering may be a separate entity but is mostly integrated with retailers and DSOs. Concerning the application part of the infrastructure, there are many retailers though a few dominate, millions of household and thousands of industrial consumers, and one regulator (the Office of Energy Regulation).

Looking at interoperability, we see that the development and enforcement of codes and standards are the task of the network companies, the producer, and the regulator. Establishment is mostly a regulatory issue, although it involves consultations among all of the mentioned entities. Applying or upholding them is the direct responsibility of producers and network companies, with the latter having the responsibility of checking gas composition. As with electricity, the regulator may or may not be directly involved in daily operations, depending on the need for regulatory oversight to ensure compliance.

The planning and facilitation of interconnection among networks is a matter for network companies. They are responsible for linkages between network segments and between the network and producers and consumers. The natural gas operator (GTS) plays a dominant role in the facilitation of interconnection due to the structure of the network; it is here where all production and foreign flows come together before they are dispersed into regional distribution networks. It also plans for future network extensions and the connection of new consumer regions and producers. The entity storage may also play a supportive role in case of emergencies, e.g. when a GOS fails.

Operational, tactical, and strategic capacity management form the heart of activities and seemingly involve coordination among all entities. Most responsibilities lie with the TSO and to a lesser extent distribution companies, while retailers act as the shippers hiring network capacity to deliver gas to customers (sometimes assisted by metering companies), producers act as gas suppliers, and traders act as intermediaries between producers and network companies that enhance overall efficiency. More precisely, operational balancing is the sole responsibility of network companies (leading and strong direct involvement for TSO and DSOs respectively), while tactical balancing also sees a key role for network companies (again a leading and strong direct involvement for TSO and DSOs respectively) but where the entity retail is also important for scheduling and producers are involved in adjusting production volumes to demand and network capacity (though not as close as in the electricity case due to less stringent time constraints and storage possibilities). Traders may support by providing short term gas supply and metering companies may play a supportive role in providing data. Storage finally plays a supportive role in that it is mostly used as a back-up once additional gas needs to be fed-in or taken out of the network. Storage in this sense is not necessarily involved in daily operations but is frequently used. Regulators finally influence this process by setting network tariffs. Strategic management involves mostly the producers and network companies since it involves generation and fuel planning. As with electricity, while producers make investment decisions on which future fuels to generate, TSOs need to consider the connection of these new power plants and other new network connections. The regulator, finally, has to approve the plans.

Managing overall system performance in terms of quantity and quality delivered involves in essence on all entities of the supply chain (besides sources). Daily operations depend mostly on producers (quantity and quality of natural gas) and network companies (ensuring no interruption). Retail and storage are directly involved in providing demand data and back-up supply. Traders and metering companies are intermediaries that support the facilitation of the infrastructure service, while consumers affect operations through their consumption patterns and preferences. The regulator sets important universal service obligations, e.g. connecting everyone that wants access, that dictate infrastructure operations. Finally, exploration for new gas reservoirs is important for estimating future availability of natural gas. An overview is given in Table 5.4 below.

Table 5.4 Contribution of entities to gas operations per technical function

Entities	Amount	Inter-operability	Inter-connection	Capacity Management	System Management
Exploration	One	--	--	--	-
Production	One	+/-	--	+/-	+
Trade	One / Many	--	--	-/+	-/+
Transmission	One	+	++	++	+
Storage	Few	--	-/+	-/+	+/-
Distribution	Few	+	+	+	+
Metering	Many	--	--	-/+	-/+
Retail	Many	--	--	+/-	+/-
Consumption	Millions	--	--	--	-
Regulation	One	-/+ or +	--	-/+	-/+

Legend: 6 degrees of involvement are distinguished from least to most:

--	No involvement.
-	Indirect involvement (entity affects operation or planning).
-/+	Supportive involvement (set ramifications, data providers, oversight).
+/-	Weak direct involvement in daily operations (entities involved in operations).
+	Strong direct involvement (key operational responsibilities).
++	Leading involvement (central coordinating entity, system operator).

5.2.2.3 Assessing Coordination Requirements

So what transactions are involved to ensure that the control mechanisms function properly and what coordination requirements do they imply? Generally, the same picture as with electricity emerges, but with some important detailed distinctions.

Regarding interoperability, one can repeat the observations of electricity. The creation of codes and standards is a long-term system level issue and the actual enforcement of standards involves the component level in the immediate term while it again may involve regulatory oversight at the systemic level in the short term. However, while it seems we have simply exchanged gas volumes for voltage levels, there is an additional issue to be checked: gas composition. Nevertheless, because checking gas composition needs to occur on the component level in the immediate term, it does not alter the coordination requirements. We thus require the same mode of organization: 'directive planning' and 'upholding general framework conditions'. Focusing on facilitation over planning, the overall criticality of interoperability matches that of medium criticality (common operation based on agreement between autonomous entities).

Concerning the facilitation of interconnection, this is a system-level issue in the short term. It is a systemic issue because network operations rely on the continuous flow of gas through the various national and regional pipeline segments and failures in the region may have national repercussions. It is a short-term matter (and not immediate term) because the possibility of gas storage provides a buffer between the transmission and distribution networks in case of connection failure that lowers response time. For example, it could enable the possibility to store gas coming from the national network and feed-in stored gas into the regional network if a transfer facility is malfunctioning. Even if this is expensive and preferably not done so in practice, the possibility exists. Of course, considering the large volume of gas flows through an interconnector, repairs would still need to be undertaken on short notice because of limitations in storage capacity. The planning for new pipeline segments and their incorporation into the whole is a long-term system level issue while it eventually may involve the development of new sections on the medium term. This would lead to a mode of organization for interconnectivity of 'directive planning' and a 'compulsory monitoring and enforced adjustment'. This entails coordination requirements of very high criticality (the need for a central coordinating center that monitors and responds).

Capacity management requires a high degree of central coordination to ensure adequate operations. Operational balancing of both gas quality and quantity needs to take place on the spot, the immediate term, and centrally for the whole system (transmission and distribution networks). Though storage possibilities may alleviate network 'stress' somewhat, creating more leeway in dealing with failures, it remains unclear in how far this allows for short-term monitoring to be sufficient for daily operations instead of immediate supervision. In the end, gas needs to flow continuously. In addition, tactical management involves a tight schedule regarding capacity utilization and monitoring of activities on the system level. In other words, a transmission operator that can exercise central control of the network is required for capacity management. Altogether the two most centralized modes of organization appear to be required: 'authorative supervision' and 'compulsory monitoring and enforced adjustment'. Strategic management by definition involves a long-term exercise on the system level considering the centralized nature of natural gas production and delivery. This requires 'directive planning'. The development of the planned facilities and capacity would then take place in the medium term. In terms of criticality, capacity management involves the highest possible, the need for a central coordinating center that dictates and supervises.

System management benefits greatly from the storage opportunities that natural gas offers and the domestic reserves the Netherlands possesses. The Groningen swing production also enhances flexibility when faced with demand fluctuations. Of course, export contracts limit flexibility, but imports from Britain, Norway, and Russia increase the function of the Netherlands as a gas roundabout and the domestic possibilities to deal with demand and supply shortages. However, despite these favorable circumstances short-term monitoring is still required to ensure that supply matches demand; yet an immediate response is not. Some medium-term preparations of sufficient strategic reserves should also be undertaken. If we also consider that this is almost by definition a systemic technical function, a mode of organization that mixes 'compulsory monitoring and enforced adjustment' and 'a controlled allocation mechanisms' seems best suited. According to the framework, this would involve a very high criticality level that requires a central coordinating center that monitors and responds.

The broader environment in which the control mechanisms operate seems to stress the need for central coordination, but also hints at possibilities for the separation of production and networks. While the Dutch natural gas network can be considered complex, with a few entry but millions of exit points and some foreign connections, the possibility for storage creates a buffer that reduces the interdependence of network segments and allows for more local flexibility. This way, small local failures may not have immediate national consequences. More importantly, demand fluctuations need not imply immediate alteration of production levels. Excessive production can be stored and is not necessarily lost. This loosens the interdependence and eases the coordination between producers and network companies. In other words, in terms of operations, they may be separate entities. This differs radically from electricity, where they constantly have to coordinate. The intensity of network usage, finally, does not appear to be extraordinary. In general, therefore control mechanisms are employed in a more forgiving environment than electricity, even though control mechanisms require central coordination. The result is captured in Table 5.5 below.

Table 5.5 Coordination requirements of technical functions for natural gas

	Interoperability	Interconnection	Capacity management	System management
Coordination requirements	-/+	+	++	+

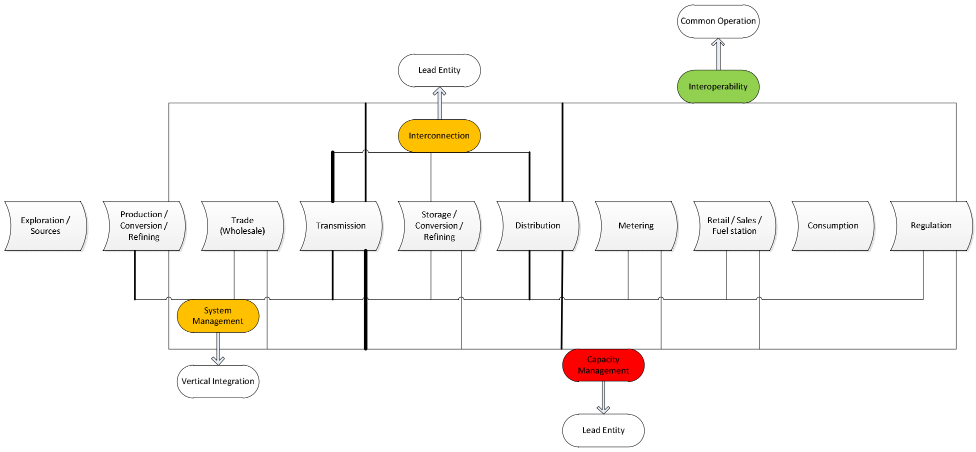
Legend: 6 degrees of criticality / central coordination requirements can be distinguished:

- - - Not critical; autonomous entities act without need for coordination.
- - Low criticality; autonomous entities that voluntarily adjust operation to a common rule/goal.
- -/+ Medium criticality; common operation based on agreement between autonomous entities.
- +/- High criticality; continuous coordination between key entities.
- + Very high criticality; central coordinating center that monitors and responds.
- ++ Most critical; central coordinating center that dictates and supervises.

5.2.2.4 Towards an Organizational Structure for Natural Gas

Combining the results of steps 2 and 3 brings us to the following organizational structures per technical function. Interoperability entails medium levels of criticality (although less instantaneous an issue here as with electricity, it has more quality issues instead) and involves many entities; this calls for ‘common operation’ as the organizational structure. Interconnection is the task of the TSO and DSOs and requires constant monitoring of linkages, while storage may play a supportive role. Considering the flow moves from TSO to DSO networks, a ‘lead entity’ structure wherein the TSO act as the leader seems most appropriate. Capacity management is also a highly critical activity. Though gas storage allows for leniency by relieving pressure or filling pipelines when needed, control of gas flows and quality requires supervision. Combined with the key role of TSO in managing gas flows (despite the importance of many actors in that process), the most suitable structure appears to be that of a ‘lead entity’. Here the difference with electricity is noticeable. The nature of production that can be more readily shut on and off and storage possibilities decouple production from transmission. Those same storage possibilities also make criticality lower for system management as compared to electricity because demand and supply need not match instantaneously. However, because tight monitoring is still required and many entities are still involved in matching demand and supply, a ‘vertically integrated’ structure follows from our logic. How appropriate this is, is rather debatable though in light of the infrastructure features. The results can be seen in Figure 5.6 below.

Figure 5.6 Towards an organizational structure for natural gas



Legend: No and indirect involvement = no line
Supportive and weak direct involvement = normal line
Strong direct involvement = bold line
Leading involvement = fat line

Not critical = white
Low criticality = blue
Medium criticality = green
High criticality = yellow
Very high criticality = orange
Most critical = red

So what does this imply in terms of organizational structure? The transmission and distribution entities seem to be the key players in technical operation and maintenance of reliability, followed by producers and retailers. This implies that the TSO and DSO entities should be at the heart of the organizational structure.[129] In addition, the high levels of criticality for capacity management and interconnection and to a lesser extent system management signal a need for central coordination. Considering the loose interdependence between network companies and producers, the central role of the TSO in network operations in relation to DSOs, and the storage possibilities for system management and interconnection, it appears that criticality is located around the network rather than throughout the entire infrastructure supply chain. The entities production and retail may be run relatively independently from network activities. Hence, despite that gas generation, consumption, and retail/metering is strongly related to the maintenance of network balance, the vertical integration of production, transmission, distribution, and retail is less required than in the electricity example. In terms of the organizational structures, this would come down to one where the TSO represents the 'lead entity'. Looking at the natural gas flows strengthens this line of reasoning; all domestic and international sources come together in the transmission

[129] According to the logic that the entities dealing with those critical technical functions that require a centralized mode of organization should become the lead entities in the overall infrastructure (and those that deal with less critical technical functions may be vertically integrated with it or separated from it, or even be completely autonomous).

net, not that of distribution. Moreover, natural gas is still mainly produced in a large-scale centralized fashion and then transported from Groningen into the country, flowing from TSO to DSOs. A counter argument to this outcome could be that natural gas only knows a single producer in the Netherlands and that it makes no sense therefore to separate it from the network since it plays such a dominant role in facilitating natural gas services. However, the possibility of the increasing use of foreign sources lessens the infrastructures' dependence on that producer (NAM), freeing the TSO up to act as a more independent system operator. Besides, coordinating production with a single producer is considerably less challenging than with many, as with electricity. Interaction might not be so complex that vertical integration is required.

5.2.3 What Organizational Structure for Petrol?

5.2.3.1 Critical Technical Functions and Control Mechanisms

Concerning interoperability, the most important issues involve the complementarity of petrol composition and the specifics of delivery trucks, storage depots, and fuel stations, and between petrol and the requirements of internal combustion engines. Considering the ease with which petrol can be transported, few if any problems are to be expected. In addition, there are no regulatory conditions to infrastructure or delivery truck access, except perhaps for some economic barriers to entry. However, there always may be new developments that need be kept track of. Examples are more efficient production and distribution means, more efficient engines, but also the use of biofuels, hydrogen, and electric vehicles that may require new hybrid engine specifications. Of course, it is likely that they will have little to do with the petrol distribution networks as such and will compete more at the retail and consumer part of the chain. In all, the development and upholding of standards to ensure infrastructure functioning seems to be a relevant, if minor, issue.

Regarding interconnection, both the facilitation of existing linkages and transport planning need to be undertaken. First, the physical links between refineries, terminals, depots, and retail stations require sufficient truck capacity, sufficient storage means at depots, and road accessibility. Considering the fact that truck delivery is not based on fixed geographical assets, petrol allows for a great flexibility in terms of transportation. Combined with storage depots, the petrol infrastructure offers very low interdependence (many buffers) between supply chain entities. From a technical perspective, anybody with a tanker truck can start buying petrol from refineries or wholesalers and deliver it to a retailer. Facilitating interconnection is hence a truck company internal issue. The interconnection between truck distribution companies may become necessary if petrol is resold from one to another; but this is an economic consideration, not a technical requirement. If so, terminals and depots play a linking role. Second, considering that the roads and trucks for distribution exist, planning for the delivery between new refineries and new retail filling stations only involves using existing transport means and capacity differently and perhaps the occasional building of new depots or distribution centers if a region shows a strong increase in demand. A system of swapping (the use of each other's distribution networks to access new markets) does indeed seem very useful for 'interconnecting' the distribution networks of different oil companies.

Concerning capacity management, there is no need for operational balancing in the sense of gas pipelines and electricity grids with their flows, pressures, and content. Tanker trucks ensure that petrol is available at the filling stations. Nevertheless, this way of distribution is not free from imperfections. Occasionally, a truck may malfunction or filling stations are sold out, so that supply is not meeting demand. While a nuisance (and the minor economic consequences should be avoided), it hardly poses a risk to the technical functioning of the infrastructure; there are sufficient alternative trucks to take its place, storage depots, terminals, and refining facilities to switch to, or other retail stations for customers to drive to for that matter. If shortages occur regularly at specific filling stations, additional truck deliveries can easily solve this problem. Yet such issues do not require the coordination among various entities; they can be done by the distribution company alone. Concerning tactical capacity management, there are some issues regarding unit commitment and maintenance. Delivery trucks need to be allocated to travel between refineries or terminals and retailers, refineries or terminals and depots, and depots and retailers. Maintenance of trucks also must be consistent with general truck availability. Some strategic capacity management is also required. New refineries, terminals, and storage depots might need to be built at other locations, more suited to efficient production and delivery. The same goes for new petrol products or competitors such as biofuels.

Finally, system management does not have a technical issue for the use of oil as a motor fuel. Regarding the matching of supply and demand, the storage possibilities of petrol, the technically flexible way of distribution, and the large amount of retailers make matching demand and supply seem effortless. Problems are only foreseen in the centrality of refineries and terminals that may act as a bottleneck for oil distribution. Though the Netherlands has sufficient refining capacity and throughput capacity at terminals, much of it is used to serve exports. Besides, their functioning and capacity levels need to be ensured. Of course, supply shortages due to oil disruptions in the Middle East are more difficult to handle. Creating strategic reserves and diversifying oil imports, avoiding dependence on just a few oil exporting countries, are possible remedies in this respect. Yet such situations are not technical in nature. The quality of service is mostly dependent on the availability and accessibility of retail stations for customers and in the future perhaps the sustainability of fuel options. Some planning in this regard by retailers and refiners might be required. Affordability is an economic issue dominated by global energy markets rather than technical operation efficiencies.

5.2.3.2 Allocating Technical Functions

So which entities are most likely to be involved based on technical considerations? According to section 5.1.3 and our focus on the downstream part of the Dutch petrol infrastructure, the entities sources and exploration, production, transmission, and wholesale trade (of crude oil) are not relevant for our exercise. However, refinement and terminals may take the place of production, as this is where petrol is made or blended and where oil or petrol enters the country. If we take this perspective, there are a few key refiners[130] and many wholesale petrol traders in the generation part of the infrastructure. The network consists of a great variety of truck distribution companies; while they may be integrated into the refiner, be dependent contractors, or act independently, we will treat here under the entity distribution. The entity storage represents the many regional depots. Metering can be ignored as a separate entity as it is performed by retailers, which number in the thousands (though many of them belong to the same refiner). Consumers rank in the millions for personal automobile users and thousands for trucking companies (we do not focus here on industrial petrol use). The regulator is the Netherlands Competition Authority.

The development and enforcement of norms and standards of interoperability are the tasks of the regulator (as the coordinator of a standardization process) and the refiners (for living up to established agreements). Distribution, storage, and retail need to support petrol standards and hence are directly involved. However, requirements for tanker trucks and depots are rather low considering the ease with which oil based motor fuels can be stored and transported. Of course, there are many standards concerning safety issues and pollution. But they are not technical / operational in nature.

The facilitation and planning of interconnection appears to be the responsibility of the truck distribution companies while storage depots assist them. Because distributors are the sole responsible for connecting the refineries and filling stations (strong direct involvement) they do not play the role of a leading entity in the sense that they dictate the operational responsibilities of other entities.

Operational balancing is not applicable to the petrol infrastructure. The tactical and strategic capacity management primarily involves the distribution companies with refiners, storage, and retailers being important partners. Unit commitment and maintenance of trucks is the operational responsibility of the distributor, while refiners are directly involved through petrol supply and retailers function essentially as meterers, passing on their supply needs to distribution and refinement companies. Storage entities support the flow of petrol throughout the country, but do not actively manage these flows. Finally, traders affect the amount of petrol available for distribution. Distributors, refiners, storage, and retailers also take care of the planning for equipment and facility allocation.

Finally, matching overall demand and supply as part of system management depends mostly on refiners (quality and quantity of refined petrol and ensuring sufficient strategic reserves), truck companies (in matching demand and supply), and storage depots (for quick access local reserves and excess petrol storage). Fuel stations/retailers are involved by signalling demand levels. Consumption patterns affect supply requirements, but consumers do not help address system management. They are hence indirectly involved in operation. Regulators may set targets regarding strategic reserves and back up facilities in case of supply shortages. Traders, finally, add flexibility to the wholesale market operation and as such may help supply match demand. The result is summarized in Table 5.6 below.

[130] Let me discuss refiners and terminals as the entity refinement.

Table 5.6 Contribution of entities to petrol delivery per technical function

Entities	Amount	Inter-operability	Inter-connection	Capacity Management	System Management
Exploration	Ignored	--	--	--	--
Refinement / Terminals (crude production is ignored)	Few	+	--	+/-	+
Trade (petrol, not crude)	Many	--	--	-	-/+
Transmission	Ignored	--	--	--	--
Storage depots	Many	+/-	+/-	-/+	+/-
Truck distribution	Many	+/-	+	+	+
Metering	None	--	--	--	--
Retail / fuel stations	Thousands	+/-	--	+/-	+/-
Consumption	Millions	--	--	--	-
Regulation	One	-/+	--	--	-/+

Legend: 6 degrees of involvement are distinguished from least to most:

- -- No involvement.
- \- Indirect involvement (entity affects operation or planning).
- -/+ Supportive involvement (set ramifications, data providers, oversight).
- +/- Weak direct involvement in daily operations (entities involved in operations).
- \+ Strong direct involvement (key operational responsibilities).
- ++ Leading involvement (central coordinating entity, system operator).

5.2.3.3 Assessing Coordination Requirements

So what is the criticality of these technical functions and what coordination is required? The petrol infrastructure seems to be radically different from the electricity and natural gas examples.

Regarding interoperability, compliance with codes and standards needs to be ensured and an eye needs to be kept on future market developments that may alter technical standards and operations. As with the other two examples, the creation of codes and standards is a long-term system level issue but the actual adherence to standards involves the component level and the short term. Because petrol distribution is not a single integrated network such as electricity and gas, but based on individual trucks, it does not have the same stringent monitoring requirements. If the petrol itself or specific components do not meet standards, it need not contaminate large portions of the network; the effects may be limited to just a single depot and a few trucks. Consequences are limited and immediate response is not required. Monitoring and short term action of course is. The role of the regulator again is dependent on whether or not compliance is a matter of self-regulation or not. If we cheat and look at the current petrol infrastructure in the Netherlands, we find that standards are well-established and that adherence to them is of self-interest to all entities. This leads to a mode of organization of 'directive planning' and 'self-monitoring and voluntary adjustment'. Focusing again on daily operations, this low criticality is covered when autonomous entities voluntarily adjust operation to a common set of standards.

Though the distribution of petrol from refineries to fuel stations in principle has interconnectivity challenges, the nature of truck distribution (with its flexible use of trucks and storage possibilities) and the fact that each step is easily technically separable (low levels of interdependence) negates possible problems. Yet the low level of criticality that this suggests is not reflected in the scope and speed involved, which would be the system level and the short term. The features of the infrastructure seem to lower criticality to that of the component level on the short term. This leads us to a mode of organization of 'self-monitoring and voluntary adjustment' by the truck company. The planning for future truck deliveries and routes between new refineries and retail stations similarly is not a high priority due to the flexibility of delivery and existence of an elaborate road network. Hence a 'competitive allocation mechanism' is sufficient. The criticality and coordination requirements are hence low; voluntary adjustment of autonomous entities (the truck distribution company).

Capacity management differs perhaps most from the previous examples. The distribution of petrol lacks the typical physical assets that mark the electricity grid and natural gas pipeline network. In turn there is no operational balancing. Tactical management, however, might require regular contracting between refiners, terminals, wholesalers, distributors, and retailers, though long-term contracts may take care of that. Daily operations are, however, carried out solely by the truck distributors. These issues seem to be caught in between the system and component level, the more so because nationwide coverage is concerned while the consequences of a truck failing remain very limited. Regardless of the scope, these matters of unit commitment involve the short term. The same dilemma as with interconnection appears to be present. Considering the low degree of coordination required with other entities by the truck distribution company and the low negative impact of a failing truck, the mode of organization of 'self-monitoring and voluntary adjustment' seems sufficient. Strategic management also requires truck companies to pay attention to and coordinate with refiners and retailers. Yet their flexibility in reallocating trucks or adding new ones, also render this issue very easy to deal with, requiring little planning as well. A 'competitive allocation mechanism' and perhaps some 'decentralized planning' should be sufficient to deal with any problems. Considering there is no need to commonly facilitate capacity management, the low criticality requires only that autonomous entities adjust their operations to common benefits.

In terms of system management, the most relevant issue appears to be the presence of sufficient oil reserves and refining capacity to meet demand. This requires some form of collective responsibility and agreements between refiners, terminals, and the regulator, who may need to intervene on behalf of national interests. Next to that, petrol quantities between retailers, refiners, terminals, and distribution capacity need to be adjusted in daily operations. While this involves the system scope in the short and medium term for facilitation and preparation respectively, petrol's storage possibilities and the flexible nature of trucks again allow for a more decentralized form of coordination: 'mutual monitoring and stimulated adjustment'. This translates into medium criticality and necessitates common operation based on agreement between autonomous entities.

The discussion above showed that the flexibility of trucks in terms of deployment and the storage possibilities of petrol considerably alter the coordination requirements of the control mechanisms that would be needed according to the scope and speed involved. Because of this the infrastructure features were integrated in the discussion of the technical functions above, instead of dealing with them afterwards. This seems a better way of presenting the coordination requirements of technical functions in such cases and might be considered as an improved way to apply this step of the framework. Let us come back to this issue in our discussion of the experiences in section 5.3.

Table 5.7 Coordination requirements of technical functions for petrol

	Interoperability	Interconnection	Capacity management	System management
Coordination requirements	-	-	-	-/+

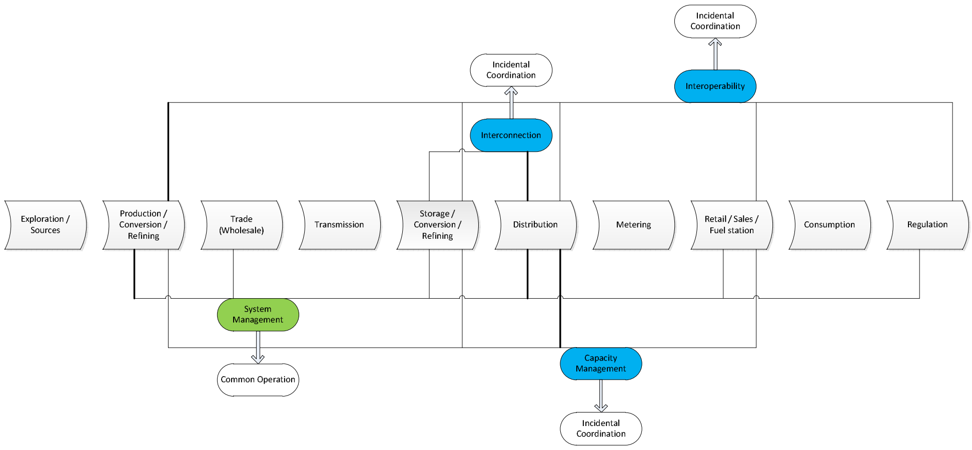
Legend: 6 degrees of criticality / central coordination requirements can be distinguished:

- \- - Not critical; autonomous entities act without need for coordination.
- \- Low criticality; autonomous entities that voluntarily adjust operation to a common rule/goal.
- -/+ Medium criticality; common operation based on agreement between autonomous entities.
- +/- High criticality; continuous coordination between key entities.
- \+ Very high criticality; central coordinating center that monitors and responds.
- ++ Most critical; central coordinating center that dictates and supervises.

5.2.3.4 Towards an Organizational Structure for Petrol

If we combine the outcomes of steps two and three for each technical function, we find that interoperability involves only low levels of criticality for future planning and can be considered not critical for current operations as adhering to standards is of self-interest to refiners, distributors, depots, and retailers. This mix of low criticality and many involved entities, but where refiners play a key role, leads to an organizational structure of incidental coordination. Interconnection is similar to interoperability; distributors are the main responsible entity for daily facilitation, assisted by depots, while criticality is low due to the truck-depot nature. Hence incidental coordination seems sufficient because distributers only really need to coordinate when new refineries and fuel stations are opened. Capacity management involves many entities with the truck distributor playing the key role. It is not a critical concern due to storage possibilities and the flexible nature of truck delivery. Incidental coordination is again the suitable organizational structure. System management, finally, involves many entities that should coordinate in order for supply to meet demand: mostly refiners and distributors, but also depots and retailers. This calls for regular contacts and the organizational structure of common operation. The result can be seen in Figure 5.7 below.

Figure 5.7 Towards an organizational structure for petrol



Legend: No and indirect involvement = no line
Supportive and weak direct involvement = normal line
Strong direct involvement = bold line
Leading involvement = fat line

Not critical = white
Low criticality = blue
Medium criticality = green
High criticality = yellow
Very high criticality = orange
Most critical = red

So, what is the resulting organizational structure? First, it appears that refiners and distributors and to a lesser extent depots and retailers are the key entities in the petrol sector. Second, the absence of high levels of criticality, i.e. the need for central coordination among entities, indicates that operation by essentially autonomous entities is sufficient. In terms of the organizational structures this would come down to a vertically separated form organization.[131] The question that remains is whether there needs to be a platform for regular consultation among refiners, distributors, depots, and retailers to ensure that the amounts demanded are supplied or that all entities may behave independently from one another and need to coordinate occasionally only. It becomes relevant here whether these entities have a long mutual history together with established patterns of interaction and sufficient knowledge about demand and supply fluctuations to warrant incidental coordination and

[131] According to the logic that the entities dealing with those critical technical functions that require a centralized mode of organization should become the lead entities in the overall infrastructure (and those that deal with less critical technical functions may be vertically integrated with it or separated from it, or even be completely autonomous).

contractual agreements on operational issues or whether petrol is a fledgling industry where these still need to be established. Considering that the petrol industry falls into the former category and that for the technical operation truck distribution is not a natural monopoly, private ownership and private operation of the network by several autonomous entities (perhaps under competition regulation) as in the incidental coordination structure seems appropriate.

5.2.4 Reflection on Results

Let us now compare the results from the framework with the current operation and governance of the Dutch electricity, natural gas, and petrol sectors. Do the organizational structures found match those of the current systems and is this in line with their respective reliability levels?

For electricity, the framework points to an organizational structure that matches the vertically integrated incumbent, mostly because of the stringent load balancing, lack of storage possibilities, and the need to match demand and supply instantaneously and continuously. What we saw in 5.1.1, however, was that the electricity sector more closely resembled the lead organizational structure, with the TSO taking the leading operational role and the other supply chain entities acting accordingly. It would then follow that if the framework is correct, the Dutch electricity sector currently does not operate under an organizational structure that is best suited to facilitate reliability. The reason for the discrepancy seems obvious: liberalization and unbundling. Though we focus on reliability only in this research, we should not forget that in practice reliability needs to be weighed against other economic, social, political, and environmental performance criteria. The Dutch electricity sector has changed greatly over the last two decades. Before unbundling, the sector was organized according to the structure found by the framework and was indeed more attuned to economies of system and reliability goals.

For natural gas, the framework points to an organizational structure that matches the one found in practice (5.1.2). Both showed the TSO as the center of a lead organization structure with other entities playing a secondary role in operation. Vertical integration of production, transport, and retail was deemed unnecessary because capacity management was alleviated by natural gas' storage and flow control possibilities, though gas pressures and composition required constant monitoring, and the somewhat lesser time constraints in dealing with unexpected events (buffers). In other words, the fragmentation of ownership and decision rights over network entities need not impair its complementary and reliable operation because the transmission operator has more means to match supply and demand himself, not needing to coordinate instantaneously with producers and retailers. This example also shows that the technical operation of natural gas networks moved along with liberalization and unbundling while retaining reliability. Whereas before liberalization there was basically one natural gas incumbent from which gas was bought and transported to Dutch households, requiring much coordination between NAM and GasUnie, after liberalization this coordination is less required because of the multiple gas sources entering the Netherlands[132], raising liquidity and giving GTS more space to manoeuvre in fulfilling its contracts. Hence, one might argue that both before and after liberalization the organizational structure suited the facilitation of reliability.

Concerning petrol, we found a very different situation than that of electricity and gas. Technical operation is not in need of central coordination due to the nature of truck distribution, requiring occasional interaction only. Yet the system is strongly vertically integrated in practice, especially evidenced by the position of several oil majors being active from refining to retail. This discrepancy can be explained by the economic rationale behind vertical integration. The history of the oil sector shows plenty of reasons, such as market power, why integration was profitable. More interesting for this research, however, is the question what the effect of the overly centralized organization on reliability levels is. Does the mismatch stifle operational flexibility, thus lowering reliability? Perhaps higher levels of central coordination do not harm technical operation but instead pose unnecessary transaction costs to achieve similar reliability levels (that in turn may be offset by the financial benefits of being a monopolist)? Or perhaps truck delivery could be more efficiently and reliably done if it were an autonomous entity?

In sum, the application of the framework has produced organizational structures that to varying degrees resemble or differ from existing Dutch energy organizational arrangements; whereas electricity was slightly different, gas was essentially the same, and petrol was very different. What matters in the end, however, are the levels of reliability in those systems[133] and whether it would fare better under the organizational structure identified by the framework of alignment or the existing organizational practices. This is difficult to establish without a counterfactual though; there simply are no two Netherlands that would allow for comparing the current with the hypothesized organizational structure and their reliability performance. Moreover, we already saw that imperfect organizational structures may be aided by more coordination efforts on behalf of the entities involved (see section 2.1). While this would increase transaction costs for maintaining reliability levels, those same levels would nevertheless be achieved and hence not show the misalignment between the organizational structure and operational reliability requirements. The best one can do is to argue the result. Finger and Künneke (2006-2008) have basically done so when they argue why certain aspects of infrastructure performance in the electricity sector have diminished after liberalization due to the institutional and organizational changes not being complemented by technical ones.

5.3 Considerations and Recommendations for Framework Application

Looking at the application of the framework thus far developed, it seems that using the critical technical functions and their subdivisions as a starting point proved very useful for giving focus to a discussion on the technical characteristics of new energy

[132] The flexibility that the wholesale gas market offers also brings the possibility to quickly find gas supplies to balance the pipeline system if needed.

[133] For an overview of Dutch energy infrastructure reliability levels please see EnergieNed 2003a and 2003b.

systems. Furthermore, the allocation of responsibilities encountered few problems. There were, however, some challenges in establishing the coordination requirements of the technical functions.[134] There are a number of experiences made during the exercise in the previous section that should be discussed at this point before we are ready to apply the framework to future energy systems. Coming to one overarching organizational structure proved feasible, even though it does seem to oversimplify matters. But this was to be expected. In all, the cases have shown that the framework provides an interesting attempt.

The first issue is the fact that there are some notable difficulties in establishing the mode of organization of control mechanisms. Though it can be forgiven that one is not always able to measure the scope and speed precisely so as to box them in one of the twelve modes of organization presented in Figure 4.2, there are issues with measurement and the categories given by Künneke et al. that pose a bigger challenge. For example, we saw with interoperability that codes and standards may be established over long periods of time, and that they in essence represent a very specific asset, which is bargained for at the (inter)national level. Once established, such consensus-seeking is no longer required, except for future revisions necessary to adapt to new developments. Even more important, while new standards might necessitate regulatory oversight to ensure compliance, as there often is still considerable possible variation in practice, established standards may not require such systemic checks since compliance to standards becomes a prerequisite for the rights to use a network. Enforcement then becomes solely a component level issue. Hence the existence of codes and standards may allow a shift of systemic coordination to a form of self-monitoring and voluntary adjustment. This matter is problematic for the framework because the existence of such standards cannot be known from just the technical characteristics of infrastructures. So how might we know whether certain standards are in place for future energy technologies? Since we cannot, it becomes necessary to assume when such standards are likely to be in place. Therefore, for the application of the framework to future energy systems the case itself needs to clearly specify whether or not codes and standards exist in order to assess whether enforcement requires central oversight or may be left to individual entities.

This brings us to a similar matter. What is the role of experience and established routines in relation to criticality? Like the considerations mentioned in chapter 4, routines and experience represent non-technical features of infrastructures that affect operations. Established operational procedures and long-standing consumption, production, and transportation patterns accompanied by continuous interaction between the same entities create an environment in which coordination is routine. One entity may know how another is likely to respond based on past experiences. Routines and experiences hence create a sense of predictability, i.e. predictable and familiar behaviour, in an uncertain environment. Such routines

[134] It is here where you can see that coherence was first used to compare institutions and technologies in a setting of an existing network where both can be studied in depth. The switch to alignment, however, seems to require more operationalization of the criteria of coordination requirements besides the scope of control and speed of adjustment), such as the features, to establish the coordination requirements of technologies.

incorporate valuable lessons and experiences that help entities cope with challenges. As such, the longer entities cooperate, the more routine developed, the less a failure is likely to end in disaster, the less criticality. Of course, too much familiarity may also give a false sense of confidence and ability. Let us therefore include routines and infrastructure maturity (as a proxy or measure for the culmination of past experiences) in the list of features to consider.

Third, the framework seems generally more suited to capacity management than to other technical functions. Whereas the scope and speed of control mechanisms faced some challenges while establishing them for interoperability, interconnectivity, and system management, they seemed well-attuned to capture the coordination requirements of capacity management. This is most notable for the coordination requirements of the various speeds of adjustment, i.e. operational balancing, capacity utilization, capacity allocation, and system transformation, which seem directly tailored to the functions of operational balancing, tactical management, and strategic management. In contrast, the scope of control seems more equally suitable to all four technical functions. They seem just as attuned to interconnection, interoperability, and system management as to capacity management. Moreover, it is more difficult to relate the various modes of organization to the control mechanisms of interoperability, interconnectivity, and system management, than to capacity management.

Finally, the establishment of coordination requirements seems caught between two different aspects of reliability: preventing failures from occurring and limiting the consequences of failure. On the one hand, control mechanisms should be in place to prevent accidents from happening and to restore normal operations if something malfunctions. An operational control center may be required to balance gas networks, for example. They represent what should be in place for reliable operations. They also entail specific coordination requirements. This research has so far been focusing on this perspective on reliability. On the other hand, the features of infrastructures highlight the propensity for cascading effects and the likely impact of an eventual failure on system operations. Tightly coupled systems may, for example, lack buffers to keep a failure in one part of the system from spreading other parts. Such a system can be said to increase in criticality as they are likely to require additional control mechanisms to ensure that a failure does not spread throughout the system. Alternatively, one could view a system which fails often, but whose failures remain limited in scope and are easily corrected as having low criticality. Petrol's storage possibility and the flexible use of trucks are a case in point here. The problem is that while the former might have a clear link to certain scopes of control and speeds of adjustment and coordination requirements, the latter leaves much room for own interpretation in the establishment of the coordination requirements of a technical function. We saw that with the matter in how far natural gas storage could alleviate network balancing operations vis-à-vis electricity, for example. Unfortunately, there is no simple answer to this. Hence the effect of features on the overall coordination requirements (next to the control mechanisms' mode of organization) has to be substantiated by solid argumentation for each separate technical function. Only then may we prevent misjudgements. To do so, we need to discuss the infrastructure features together with the scope of control and speed of adjustment of control mechanisms in the third step of framework application.

5.4 Conclusion

This chapter applied the framework for alignment to three contemporary cases: the electricity, natural gas, and petrol infrastructures in the Netherlands. The immediate aim was to see whether it could produce organizational structures that complement the technical characteristics of these infrastructures and that make sense in the light of reliability. The broader aim was to improve or refine the framework based on the results and experiences of the application. After a brief introduction to the Dutch energy sector, the three energy vectors were specifically addressed to highlight their technical and operational specifics. These then served as the starting point for the four steps of the framework. The outcomes of the framework differed in their resemblance to the organizational structures currently in place. Whereas the organizational structure found by the framework for natural gas matched that in practice (lead organization), electricity was slightly different, although at least still in the centralized category (vertical integration instead of lead organization), and petrol was radically different (incidental coordination instead of vertical integration). This led us to suspect that reliability improvements could be achieved in these infrastructures if we were to implement the organizational structures proposed by the framework.

After the application, four issues were addressed that had proved challenging: a) the establishment of fitting modes of organization, and in turn coordination requirements, might be dependent on non-technical factors; b) the neglect of routines and experiences as a feature determining criticality, c) the better suitability of the speeds of adjustment to capacity management vis-à-vis other technical functions, and d) the important but difficult classification of features' effect on coordination requirements. All four were related to the third (yet core) step of the framework. The other three steps proved less troublesome and altogether promising. The critical technical functions proved a good starting point for unravelling the technical characteristics of future energy systems. The allocation of technical functions to the responsible entities proved very useful in identifying their degree of involvement. The combination of all technical functions, their responsible entities, and their coordination requirements into one organizational structure went smooth at the hand of the guiding reasoning adhered to, though it was achieved with the help of some strong simplifications. With these final considerations we believe the framework to be ready for application on a future energy system and the transition thereunto.

Part III

6. A Transition to Hydrogen in the Netherlands

This chapter introduces the practical illustration of the introduction of a renewable energy source or carrier and accompanying infrastructure: a roadmap towards the use of hydrogen as a motor fuel for personal transportation in the Netherlands.[135] By addressing the technical characteristics of a hydrogen infrastructure during the various stages of a transition, we add some meat to the conceptual skeleton that transition theory and the overview on infrastructure development set up in chapter 3 and present a technical case to apply the framework for alignment on. Concerning the roadmap, we follow the pathway developed by the Energy research Center of the Netherlands (ECN) for the European Union's (EU) HyWays project. In doing so, the focus is on hydrogen as a motor fuel only, neglecting stationary applications, the reason being that hydrogen is mostly considered an alternative to petrol in the transport sector and other applications are contributory.[136] SenterNovem (Hoogma 2005) also comes to similar conclusions in this respect. Before describing the roadmap, some background knowledge on hydrogen and the Netherlands is useful. To this end several matters will be addressed: why make a transition to hydrogen and what effort has the Dutch government undertaken in this direction; what are hydrogen's technical characteristics, how are the various infrastructure components connected, and what does a transition entail; finally, what does a Dutch hydrogen infrastructure at various stages in the roadmap look like?

6.1 Towards Future Renewable Energy Systems in the Netherlands

According to the International Energy Agency (IEA 2009, 9), energy policy should balance energy security, environmental sustainability and economic growth. Dutch energy policy explicitly addresses these three aspects by pursuing a reliable, clean, and affordable energy system. With regard to the 'clean', the government has recently laid out an ambitious energy and climate agenda under its *Clean & Efficient Programme* (2007), its *Energy Report 2008 strategy*, and the *Energy Transition Framework*. Combined these aim for lower CO2 emissions, increased renewable deployment rates, and an increase in energy efficiency. The core target for renewables is a 20% share in the overall energy mix by 2020 and completing a 'big step' in the transition towards a more sustainable energy system by 2020. The policy and institutional framework for the development of sustainable energy technologies in the Netherlands is anything but standard; it takes place in 'regular' energy policy as well as the so-called Energy

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[135] This chapter is not concerned with the likelihood of success of hydrogen or the policies related to that. It is, however, interested in the pathways along which hydrogen's technical development and deployment is envisioned in the Netherlands.

[136] According to the EU HyWays (2007, 27) project, hydrogen in the Netherlands has only a chance in the transport applications as competition from electricity and gas for stationary applications is too stiff. This statement is somewhat supported by Zhao and Melaina (2006) who see hydrogen as mainly proposed to address transportation-related challenges, such as urban air pollution, global climate change (emissions), and dependence on foreign oil and gas.

Transition Framework or Energy Transition Project (ETP).[137] Let us take a brief look at both.

Concerning 'regular' energy policy, the *Clean & Efficient Programme* (2007) and the *Energy Report 2008 strategy* provide the main targets and objectives. In the Clean & Efficient Programme, the Dutch government has set the following sustainability goals: a 30% reduction in greenhouse gas emissions from 1990 levels by 2020 (mostly CO2-related), 20% renewables in the energy mix by 2020, annual energy efficiency improvements of 2% (double the current rate) by 2020 and completing a big step in the transition towards a more sustainable energy system by 2020 (IEA 2009, 112). These targets are a derivative of those set within the EU context. Interestingly, the 20% renewables target for 2020 actually goes beyond the proposed national target of 14% renewables in total energy consumption by 2020 under the overall EU framework. To achieve these goals, coal-fired power plants with carbon capture and storage (CCS) play a crucial role and are foreseen to play a very prominent role in the country's energy mix by 2030. The same goes for biofuels; the European Commission has proposed a binding target of reaching 10% biofuels in the transport sector by 2020. However, the "future for nuclear, which provided 3.5% of electricity in 2006, is less clear" (IEA 2008, 17), especially since the Fukushima disaster in Japan in March 2011. The Energy Report 2008 (prepared every four years) sets out the country's energy and environmental policy framework and the government's energy strategy through 2011 and a long-term vision to 2050. It foresees the further development of the Netherlands as a hub for energy, especially natural gas; the expansion of smaller-scale energy technologies, including renewables; the expansion of coal-fired power plants with carbon dioxide capture and storage (CCS); the development of a new generation of nuclear power stations; a transition from passenger vehicles fuelled by petrol and diesel to those fuelled by electricity, biofuels or hydrogen[138]; a dramatic reduction in the energy needs of buildings; and the development of more sustainable heat for use in industry (IEA 2009, 21).

To achieve these ambitious goals, the Dutch government increased annual budgets for energy and climate policy and plans to spend over 900 million euro on energy research and demonstration projects between 2008-2011 under its innovation agenda (Energy Report 2008; IEA 2009, 130). Research funding for new energy technologies has also been increased in the Netherlands since 2003. This was mostly to the benefit of renewables, energy efficiency, and carbon capture and storage technologies. The Ministry of Economic Affairs is the main financer for energy R&D, "consistently providing around 90% of the total budget in recent years" (IEA 2009, 129). In 2005 and 2006, the main beneficiaries of these funds were executing institutions such as private companies (40%), universities (10%), and institutes such as

[137] Following Kern and Smith (2008, 2) the "energy transition policy is here used as a term to summarize all activities initiated by the ministry of economic affairs to implement 'transition management' in energy policy following the National Environmental Policy Plan."

[138] "Under the EU Directive 2003/30/EC, the Netherlands has an indicative (i.e. non-binding) target to provide 5.75% of road transport fuels from renewable sources by 2010" (IEA 2009, 42).

ECN and TNO (nearly 50%) (IEA 2009, 130).[139] Intermediaries such as SenterNovem and NWO play a crucial role in the distribution of public funds. "[L]ike many smaller countries, the Netherlands directs public R&D funding towards longer-term basic science research, leaving the deployment and commercialisation of energy technology largely to the private sector" (IEA 2009, 128), with the notable exception of CCS where the government also seems to play a larger role in deployment.

In contrast to the above, the Energy Transition Project aims at supporting the transition process to a more sustainable energy future, rather than setting goals, determining funding, and making policy. The ETP was initiated by six ministries and involves their cooperation with private parties, scientific institutes, civil organisations, and government agencies (IEA 2009, 20-22; EZ 2004). The introduction of the ETP followed the development of a new literature in science on socio-technical systems and transitions, as we saw in chapters 2 and 3, and led to the development of transition management as the governance perspective to facilitate such a transformation. Transition management treats institutional design as an innovation process where technologies and institutions co-evolve and intends to inject "goal-directing processes into socio-technical transformations" (Kemp and Loorbach 2006, 22). It is hence more of a governance perspective than an instrument to obtain predefined policy outcomes (Rotmans et al. 2000-2005; Kemp and Rotmans 2004; Leach et al. 2007; Scoones et al. 2007; Smith and Stirling 2008; Verbong and Geels 2007). This entails a very different view of how to develop renewable energy technologies from the more common project managerial approaches and makes the Netherlands a special case when it comes to the organization of efforts towards sustainability. Key in the proposed perspective are energy transition platforms where various public and private stakeholders continuously re-address visions, transition paths and experiments in an iterative and reflexive manner consisting of four phases: 1) organizing a multi-actor network, 2) developing sustainability visions and transition agendas, 3) mobilizing actors and executing projects and experiments, and 4) evaluating, monitoring and learning (Kemp and Loorbach 2006, 17; Rip 2006). As a consequence, under transition management transitions are always starting and ending as an ongoing evolutionary process. Finally, once a dominant technology emerges, transition management advocates "control policies to put pressure on the existing regime […] to bring about transitions" (Kern and Smith 2008, 2). This focus on the institutionalization of new technologies poses a step forward from the energy policies of the 1990s based on bottom-up, market oriented approaches and the energy policies of the 1980s based on a top-down, central control oriented approach because it not only looks at market incentives and technology push policies, but also tries to create a framework where government policy makers, industry stakeholders, non-governmental organizations (NGOs), and scientific institutes actively pursue accompanying institutional changes to ensure the emergence of a new energy system.

The Fourth Dutch National Environmental Policy Plan (2000) provides the starting point for both a transition towards a more sustainable energy system and the

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[139] NWO stands for the National Organisation for Scientific Research, ECN for Energy research Centre of the Netherlands, and TNO for the Netherlands Organisation for Applied Scientific Research.

introduction of transition management as the governance framework. The Ministry of Economic Affairs (EZ), in charge of energy and innovation policy, has taken the role of 'transition manager'. The heart of the energy transition project is currently based on seven transition platforms[140] where public and private actors meet[141] to develop shared visions, pathways and experiments: new gas, chain efficiency, green resources, sustainable mobility, sustainable electricity, the built environment and the greenhouse as energy source (SenterNovem 2009). Most of the seven themes stem from consultations among existing energy sector incumbents and scenario studies conducted under the long-term energy supply strategy project drawn up in 2000 (Kern and Smith 2008, 3).[142] In addition, EZ started in 2002 with the Project Implementation Transition management, which aimed to find out whether the various themes would have enough "support, enthousiasm and commitment" from the relevant stakeholders (Kemp and Loorbach 2006, 19). The beginning energy transition also led to the policy renewal project wherein the government looked for new energy policy instruments and redefined its relationship with society and business (Kern and Smith 2008, 4). It has led to a more participatory and interactive form of governance.

After these initial developments, the Ministry of Economic Affairs started to develop the themes into strategic visions in 2003-2004. To this end, public-private transition platforms were established for each theme and stakeholders recruited from existing policy networks were tasked to work out "possible transition pathways along which an energy transition can be achieved" (Kern and Smith 2008, 3). Since 2005 the first transition pathways are explored in technological niche experiments carried out by stakeholder coalitions. 2005 also saw two major organizational changes to the energy transition project. First was the introduction of the taskforce energy transition, consisting of high-level members from Dutch industry and the public sector, to complement existing platforms. Second was the creation of an interdepartmental directorate energy transition, encompassing civil servants from various relevant

[140] The IEA (2009, 128-129) sums them up nicely. *Green raw materials*: production and use of plant-based materials, including biofuels. *New gas and clean fossil fuels*: more efficient applications of natural gas and other fossil fuels. The platform also includes the development of synthetic natural gas (SNG), biogas and hydrogen. *Sustainable electricity supply*: developing new, clean and reliable sources of electricity, such as offshore wind, solar or biomass-based electricity. *Sustainable mobility*: accelerating market deployment of alternative motor fuels, such as natural gas and biofuels, as well as new, environmentally clean vehicles (for example, hydrogen-powered). Sustainable mobility also focuses on vehicle guidance systems to prevent traffic jams. *Chain efficiency*: tackling energy use at the chain level – organising industrial production chains more intelligently. The *built environment*: making heating and cooling of buildings more sustainable and climate-neutral. This platform aims at introducing new technologies, including solar heating and underground heat and cold storage. *Greenhouses as energy sources*: reducing fossil fuel use in the Dutch greenhouse horticulture sector.

[141] Primarily private-sector and research community participants (Kern and Smith 2008, 5).

[142] These platforms, or energy themes, supported the development of the government's Clean & Efficient programme to 2020, its Innovation Agenda, the government's Energy Report 2008, and (obviously) it's Energy Transition Framework to 2050.

ministries.[143] While the taskforce is essentially an advisory group that oversees the transition process, identifies strategic directions and aims to "strengthen the role of the platforms" (Kern and Smith 2008, 3), the directorate aims to integrate transition policy and ongoing policies. On 25 February 2008, the *regieorgaan energietransitie* or directing organ energy transition succeeded the taskforce as the leading body of the energy transition for the coming five years (SenterNovem 2009). The organ's[144] main task are to advise the government on how to best facilitate the market, create support for the transition from public and private actors, guard the coherence among the various platforms and experiments, and prioritize promising pathways. Whereas the taskforce aimed at sketching ambitions, planning visions, and creating a high profile for the transition, the organ focuses on the execution and has therefore a more directing character.

Since the National Environmental Policy Plan (2000) the Dutch cabinet has stated the ambition to achieve a sustainable energy system by 2050 by means of an energy transition on several occasions. The development and deployment of hydrogen as an 'alternative motor fuel' in combination with fuel cell vehicles is considered a possibility in this respect. Hydrogen can make mobility sustainable because it can be produced and distributed in a CO2 neutral manner, thereby addressing climate change, and its use in fuel cell vehicles leaves solely water vapour as an exhaust gas, limiting air pollution in urban areas. Next to that, hydrogen could contribute to supply security as it can be produced in a variety of ways and by a variety of sources and is hoped to lead to innovation in a number of hydrogen related technologies, creating cutting-edge export products. As such, hydrogen harbours great promises in dealing with current environmental and geopolitical concerns surrounding the affordability, availability and safety of energy (McDowall and Eames 2006, 1242-1243). However, the sense of urgency in social and environmental dimensions for an energy transition is not matched by economic and technical opportunities. Currently, road transport is very much based on fossil fuels to which hydrogen and fuel cell technologies are rather costly and immature in comparison. In addition, the absence of a hydrogen refuelling infrastructure on the one hand and that of fuel cell vehicles on the other creates a 'chicken and egg' problem because building one without the other serves no purpose (McDowall 2007, 12-13; McDowall and Eames 2006, 1242-1247).

So, where does hydrogen fit into the policy picture? In essence there is no specific hydrogen (or fuel cells) program or unified Dutch policy (Hoogma 2005). On the one hand, hydrogen is part of two of the seven themes developed by the Ministry of EZ in light of the energy transition project: 'new gas' and 'sustainable mobility'. While hydrogen plays a role in the former as a cleaner of gas to be used in stationary applications, in the latter it takes a more prominent position as a replacement for petrol and diesel (although it is definitely not the only option there). Actually, in both

[143] Economic Affairs (EZ); Housing, Spatial Planning and the Environment (VROM); Transport, Public Works and Water Management (V&W); Agriculture, Nature and Food Quality (LNV), Finance (Fin); Development Cooperation (OS) (part of Foreign Affairs).

[144] It consists of the seven platform chairs, three independent members, and the organ's own chairman.

platforms hydrogen is only one of four working groups (the area of green gas in the new gas platform) and one of four pathways (driving on hydrogen in the sustainable mobility platform).[145] Next to that, other ministries (Housing, Spatial Planning and the Environment (VROM); Transport, Public Works and Water Management (V&W)) are looking into hydrogen for their interests in CO2 emission reduction and alternative fuels respectively. On the other hand, hydrogen research is conducted outside of the transition project framework as part of energy R&D policy at research institutes and universities. The NWO/ACTS Sustainable hydrogen program and H2 dialog are good examples of this. Internationally, the Dutch participate in the CUTE project (a demonstration project in Amsterdam with hydrogen buses) and a number of EU projects such as HyWays (pathways), Naturalhy (mixing with gas), Storhy (storage), EIHP (mobile and infrastructure) and HySafe (safety) (SenterNovem 2005). For an account of EU activities regarding hydrogen, please see Fernandes et al. 2005.

The status of hydrogen research in the Netherlands can be summed up this way: there exists an abundance of knowledge on hydrogen production and distribution, while for applications there is a lack thereof (Senternovem 2004a, 2004b). In general, the focus of technical research has so far been on hydrogen production (mostly reforming and local production for micro-CHP), distribution (mixing with gas), storage (diverse), and stationary applications (PEM and SO fuel cells) (SenterNovem 2005). Fuel cells (FC) and their applications are developed by technology institutes such as TNO and ECN and by a few engineering companies such as Stork, De Schelde, and Nedstack (Suurs 2009, 148). Interestingly, the little research in applications focuses mostly on stationary fuel cells, not the transport applications one might expect from the hydrogen pathway presented in section three of this chapter, which explicitly leaves out stationary applications (HyWays 2007, 27). This also contradicts the view of SenterNovem on hydrogen in the Netherlands which sees transport applications as the most viable ones (Hoogma 2005). The focus on stationary fuel cells is mainly due to the fact that the Netherlands has ample experienced companies in petro-chemical industries (Shell, GasUnie, Akzo Nobel etc.) and the port of Rotterdam functions as one of the main refineries and distribution centers of oversea oil products. Indeed, the existing gas infrastructure, the large chemical industry, and a solid knowledge-infrastructure all contribute to the upstream expertise (Hoogma 2006; Denys 2009). Consequently, "Dutch fuel cell research is internationally recognised for its quality" (Suurs 2009, 148). Downstream the picture is very different however. The absence of a Dutch automobile industry and small military industry is most notable here. The Netherlands simply is a small country. Knowledge about fuel cells vehicles therefore is dependent on foreign research. This limits Dutch government's scope of influence. Where it can realize changes in production and distribution domestically in coordination with stakeholders, it is dependent on the foreign production of fuel cell vehicles to deliver the applications. Considering the lack of a large domestic market, export markets for Dutch hydrogen

[145] The share of hydrogen experiments is rather low, however. Under the new gas platform only one out of twenty-two projects relates to hydrogen according to SenterNovem (2009). For the sustainable mobility platform, none of the seven projects carried out involves hydrogen directly, although they might affect hydrogen's prospects.

technology, knowledge, and products become important to compensate for the lack of a demand-side automobile industry. Non-technical research has so far largely focused on safety and public acceptance studies on the one hand and developing pathways and the accompanying policy tools to support the deployment of hydrogen in the market place on the other. Interestingly, the organizational requirements of hydrogen infrastructures have been largely neglected. Next to that some demonstration projects have gotten underway. Most notable is the CUTE project in Amsterdam and the mixing of hydrogen into natural gas pipelines on Ameland.

Of course, hydrogen is not only a thing of the future. Currently, hydrogen is produced and distributed by the major natural gas and oil companies, like Gasunie and Shell, and by related actors such as Air Products and Air Liquide. The same players are active in hydrogen storage as well, "although here strong connections exist with technology institutes, universities and car manufacturers" (Suurs 2009, 148). The most prominent consumers are "energy utilities, public transport companies, and (foreign) car manufacturers" who use hydrogen and fuel cells in CHP systems and as a power source in FCVs respectively (Suurs 2009, 148). Until recently, demand was almost fully subsidized. Now, first "(near)-market applications in forklifts and back-up systems" have slowly started to emerge (Suurs 2009, 148). Due to government pushing the development of fuel cell technologies, the PEM fuel cell for mobile applications in particular has seen a boost in attention since 2000 under concerns about climate change. However, fuel cell vehicles (FCVs) are hardly paid attention to for the reasons noted above. A last important note on these efforts is in order. Hydrogen and fuel cell technologies have been developing since the late 1950s in the Netherlands and are basically still in an early stage of development (the first or perhaps second if one considers the four stages of transition theory). Moreover, market deployment for both has remained rather constant at about ten years into the future for over a decade (Suurs 2009, 143). This indicates an uncertain future for hydrogen in the Netherlands.

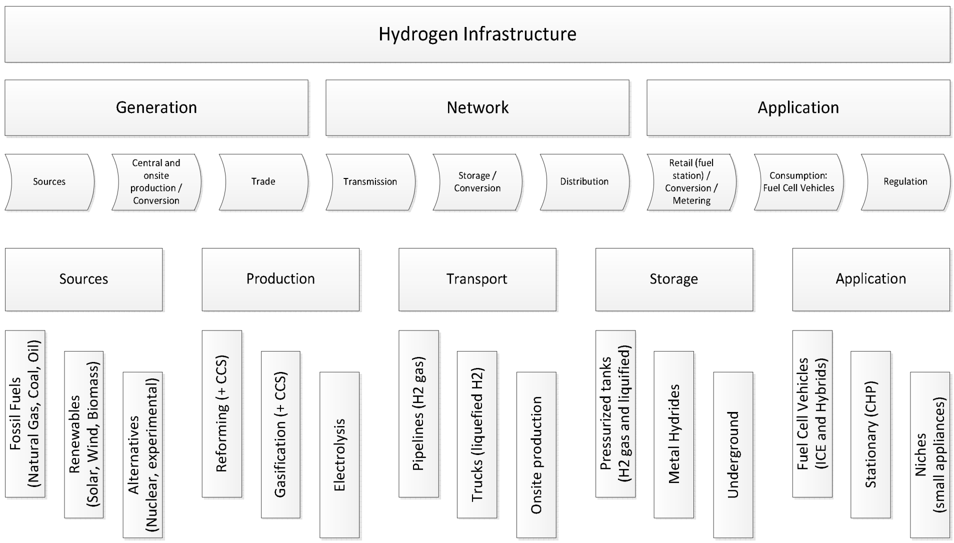
6.2 Hydrogen Infrastructures

A 'hydrogen economy' is commonly defined as an energy system in which energy is stored and distributed as hydrogen. According to Shackley and Green (2007, 225, 230-232), moving from a hydrocarbon to a hydrogen transport system involves a "replacement of a set of interlocking technologies by an alternative array of interrelated technologies which fulfil the same, or similar, functions." In our case, technology refers to the artifacts involved in the supply chain, e.g. hydrogen sources, production facilities, storage and conversion means, transmission and distribution networks, filling stations, and fuel cell (vehicle) technologies. This raises some questions, because according to McDowall et al. (2007, 1) "the literature exhibits strong disagreements about the form that a future hydrogen economy should take. […] In short, there is no single, shared vision of a 'sustainable hydrogen economy'. Rather, different organizations and individuals produce visions and expectations of possible hydrogen economies that reflect their own interests and values."

6.2.1 Hydrogen Technologies and Infrastructures

Without getting distracted by the precise technicalities, a presentation of the hydrogen supply chain is in order to understand the workings of hydrogen infrastructures. Three core issues shape hydrogen as a motor fuel (Lovins 2003; Dunn 2002; Bleischwitz and Fuhrmann 2006; Blanchette 2008; Cherry 2004; Hedenus et al. 2010; Momirlan and Veziroglu 2005): 1) hydrogen is an energy carrier, not an energy source; 2) hydrogen is very versatile, because it can be produced from a variety of sources and in a variety of ways, can be distributed and stored using different means, and can be used for a variety of end-use applications; and 3) efficient hydrogen usage requires fuel cell technologies instead of internal combustion engines for vehicle use. As such, a hydrogen infrastructure supply chain contains various parts with various possibilities. See also Figure 6.1 below.

Figure 6.1 The hydrogen supply chain[146]



Hydrogen is the most abundant element in the universe, comprising up to 70-75% of the Earth's surface. It does so not as a separate element, but "in combination with oxygen in water, in combination with carbon in a range of hydrocarbon fuels, and in combination with carbon in plants, animals and other forms of life" (Dunn 2002, 243). As such, hydrogen is an energy *carrier* like electricity or gasoline, not an energy *source* like oil, coal, wind, or the sun (Lovins 2003, 4-5). The most prominent hydrogen sources are fossil fuels such as oil, coal, and gas, alternative sources like biomass and nuclear energy (combined with water) as well as renewable sources such as wind, solar, hydro, and geothermal energy (again, combined with water). Pure hydrogen is

[146] This model only provides the main possibilities.

'colorless, odorless and tasteless' and needs to be freed from its chemical bonds with carbon or oxygen if it is to be used as an input or feedstock to a variety of industrial processes (Dunn 2002, 244). During this conversion/production process, a loss of energy occurs; e.g. electricity is needed to electrolyze hydrogen out of water. However, this loss of efficiency is hoped to be regained on a wells-to-wheels basis by a more efficient conversion process in the end-use of hydrogen. Fuel cells, as we will see, have a higher efficiency than internal combustion engines.

The production of hydrogen knows a wide variety of processes: "using heat and catalysts to reform hydrocarbons or carbohydrates, using [renewable or nuclear] electricity to split water, through the gasification of coal [and biomass] and more experimental processes involving sunlight, plasma discharge and micro-organisms" (Lovins 2003, 5). Currently the steam reforming of fossil fuels (SMR) and in the medium term the gasification of coal and biomass are the most competitive options, but also the most polluting in terms of emissions.[147] Of course, carbon capture and storage technologies (CCS) can remedy this problem, but they would increase the costs while some concerns around sequestrations environmental impact remain. Using renewable sources on the contrary is environmentally friendly, but it is only expected to produce the necessary amounts at an affordable price after large investments and in the very long term. The overall energy efficiency of electrolysis is also less than that of reforming. Nuclear electricity takes somewhat of a middle position in terms of competitiveness and cleanness, but has to overcome acceptability, risk, waste, and construction cost issues (Dunn 2002, 244-246 and EC 2003). In the long run, if supply security and costs are the main concern, coal gasification with CO2 sequestration are likely to become the main method to produce hydrogen. If clean energy and health are the primary concerns, then renewables take center stage.

The common way to transport hydrogen currently are tanker trucks carrying liquid hydrogen, using double-walled insulated tanks to limit the amount of boil-off. This is similar to the way motor fuels, all refined oil products, are transported today. The distribution by tanker trucks is generally used for medium amounts and large distances. Liquid hydrogen can also be distributed as metal hydrides loaded onto a truck or railcar, especially suited for short distances. Like with production, the liquefaction of hydrogen gas costs energy, as hydrogen only becomes a dense liquid close to zero Kelvin. Hydrogen can also be transported as a compressed gas using pipelines, cylinders, and tube trailers. The most efficient way to transport gas is through a network of (underground) pipelines, but the initial expense of installation needs to be overcome, and the hydrogen pipelines need to be able to handle the lower density and higher diffusion rate of hydrogen gas relative to natural gas (to avoid

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[147] According to the US DOE worldwide hydrogen production was at 400 billion cubic meters a year in 2003. This equals about 360 million tons of oil a year, or about 10% of total global oil production. Thus, hydrogen has about a 3.5% share in global energy. Hydrogen is commonly produced at oil refineries and in the chemical industry and used as a petroleum refinement feedstock. It is also used to make industrial commodities such as plastics. Only "about 5% is traded on the market as a liquid or gas by truck or pipeline, which is enough to fuel a fleet of 2-3 million fuel cell vehicles" (Dunn 2002, 244).

embrittlement). Pipelines are ideally suited to handle large quantities and long-distance energy transmission (Dunn 2002, 247-248). This is similar to the way natural gas is transported today. In the future, cylinders and tube trailers will become available, but high-pressure compression is required, limiting general use to small quantities and short distances.

Concerning storage, hydrogen is typically compressed and stored in gas cylinders or spherical containers, both above and below ground, or on board vehicles. Compressed hydrogen gas is the simplest and cheapest method for on-board vehicle storage. However, there are concerns about its low storage density, which is one-tenth that of gasoline. Higher storage pressures to remedy this raise both costs and safety issues. Compressed gas is generally used in small quantities and can be stored for the short term only, unless stored underground. In addition, hydrogen can be liquefied for storage at very low temperatures, where it becomes a dense liquid. Although transportation costs are lower than for compressed gas, the production of liquefied hydrogen is four to five times as high due to higher electricity needs. More futuristic possibilities are storage of hydrogen in metal and chemical hydrides and carbon structures. Although in the early stages of development, these methods promise to store hydrogen at atmospheric pressures and room temperatures. However, metal hydrides are heavy, have low densities, require energy to refill, and are comparatively costly. And while chemical hydrides offer the advantage of using the existing transport and storage infrastructure and commercial technology, and having a relatively easy liquid and storage handling, their technical and economic competitiveness is lacking. Hence, so far promises remained unfulfilled and its use contained to small quantities (Dunn 2002, 246-247 and EC 2003). Other potential means include storage in abandoned oil and gas fields, aquifers, and salt caverns (Dunn 2002, 246-247).

Concerning hydrogen applications, it is important to note that hydrogen is the lightest and smallest element. Molecular hydrogen is eight times lighter than natural gas. Per unit of energy contained, it weighs 64% less than gasoline or 61% less than natural gas: 2.2 pounds (1 KG) of hydrogen has about the same energy as 6.2 pounds of US gasoline. But the downside of its lightness is bulk. Per unit of volume, hydrogen gas contains only 30% as much energy as natural gas at atmospheric pressure (1 bar). "Hydrogen thus is most advantageous where lightness is worth more than compactness", as in vehicles (Lovins 2003, 5). Others, however, point to the fact that while hydrogen production from energy sources is relatively simple, its volumetric energy density makes it inherently expensive to transport, store, and distribute – all strong disadvantages for a transportation fuel (Zhao and Melaina 2006). Hydrogen can be used for a wide variety of transportation applications. It can be used in automobiles, shipping, vehicles (trucks, fork lifts, motor-cycles, buses) and air / space applications. Automobiles are expected to be the most important mobile application in the Netherlands, accounting for over 85% of traction use (SenterNovem 2004a, 23).

Hydrogen can be transformed into motive and heat power through internal combustion engines (ICE), hybrid electrics or fuel cell engines. In this research we focus on the latter as it provides the most clean and efficient use of hydrogen as a motor fuel and dominates hydrogen roadmap discourse. A fuel cell is "a device that converts hydrogen gas into electricity through an electrochemical reaction" (Suurs 2009, 143).[148] Please see also Figure 6.2 for more information. In terms of cost per mile driven, the efficiency of fuel cells becomes paramount to the overall competitiveness of hydrogen vis-à-vis fossil fuels and internal combustion engines. As "fuel cells are not subject to the same thermodynamic limits as fuel-driven engines, because they are electrochemical devices, not heat engines", one cannot simply compare the two (Lovins 2003, 5).[149] On the one hand, hydrogen combined with fuel cells is about 2 to 3 times as efficient as gasoline and ICE in converting energy into motion on a gallon-equivalent (in energy content), allowing one to drive that much further.[150] On the other hand, "hydrogen costing several times as much as gasoline per unit of energy contained can thus cost the same per mile driven" (Lovins 2003, 6).[151] Next to that, while fuel cells are more silent and efficient than ICEs, their life span and costs leave much to be desired (EC 2003). Fuel cells are most ideally suited to the use of hydrogen (most efficient conversion) but are also the most technically challenging. The transition to hydrogen is hence intended to move from the use of hydrogen in ICE to hybrids to fuel cell vehicles (FCVs). Here one important aspect needs to be taken into account that influences the nature of the infrastructure: on-board reforming is not preferred by the automobile industry, making on-board hydrogen storage necessary (SenterNovem 2005, 16). Thus it becomes imperative that there exist ways to integrate small, inexpensive, and efficient FC into vehicles, to design tanks that store hydrogen on-board, and to develop an infrastructure for producing and delivering hydrogen.

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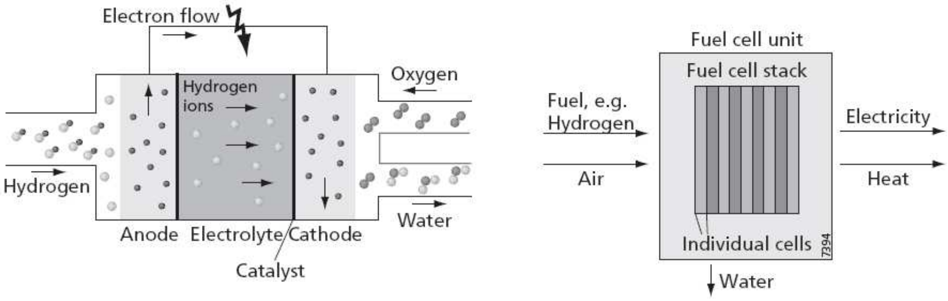
[148] A fuel cell is essentially a battery, "albeit one that works with a continuous supply of fuel" (Suurs 2009, 145). Various fuel cell technologies can be distinguished: a) Phosphoric acid (PAFC); b) Molten carbonate (MCFC); c) Solid oxide (SOFC); d) Direct methanol; e) Alkaline (AFC); and f) Proton exchange membrane (PEM) (Dunn 2002). Although hydrogen is used in most designs, it is also possible to use methanol or natural gas. "Fuel cells can be utilized in zero-emission vehicles for the transport sector [but may also] be applied in power plants, as a means to produce heat and electricity in an efficient and clean way" (Suurs 2009, 143). Low-temperature fuel cells operate only with clean hydrogen and oxygen to ensure efficiency and long-term functioning, and are hence mostly used in FCVs, whereas high-temperature fuel cells can operate longer and efficiently also with less clean or pure sources, making them more suited to use in CHP applications (Suurs 2009, 147).

[149] "Fossil fuels are traditionally measured in cost, volume or mass per unit of energy content" (Lovins 2003, 5).

[150] "Depending on how it is designed and run, a good fuel-cell system is about 50-70% efficient, hydrogen –to-electricity, while a typical car engine's efficiency from gasoline to output shaft averages only about 15-17% efficient" (Lovins 2003, 5).

[151] The well-to-wheels analyses of hydrogen for fuel cell vehicles has led to heated debates on the overall efficiency and costs (Bossel and Eliasson 2003; Bossel 2006; Contestabile 2010).

Figure 6.2 Functioning of a hydrogen fuel cell (left) and fuel cell unit (right)[152]



Source: Suurs 2009, 146.

The use of fuel cell vehicles based on hydrogen also necessitates the building of filling stations that can cover the national road network while being preferably close to local distribution centers and networks of hydrogen sources. Additionally, there need to be enough fuel cell vehicles on the road to economically warrant the building of filling stations (the same goes for pipelines). This creates a 'chicken and egg problem', as no company will build cars without filling stations, while no one wants to build filling stations without hydrogen cars. This is the core dilemma facing the economic deployment of hydrogen as a motor fuel. Additionally, compared to gasoline on-board reforming, direct hydrogen vehicles have long-term societal and environmental benefits, but using the former is cheaper, hence the threat of a lock-in. Other issues to consider are the considerable investment costs needed for automobile companies to rebuild existing product lines and the scarcity of personnel with the necessary know-how in, for example, garages for maintenance and repair.

It is important to realize at this point that the various hydrogen production, distribution, and storage technologies allow for a variety of infrastructures. Nevertheless, despite this versatility hydrogen infrastructures can be roughly divided

[152] The process is described by Suurs (2009, 145-147): a "fuel cell consists of two electrodes (an anode and a cathode) separated by an electrolyte. […] Hydrogen gas flows into the fuel cell at the anode side and is split into protons (positively charged hydrogen ions) and electrons. On the side of the cathode, oxygen flows into the fuel cell. The hydrogen ions are pushed into the electrolyte whereas the electrons (being unable to pass the material) are led through an electric circuit. The electrons and hydrogen ions meet at the cathode where they are recombined with oxygen (which is split into negatively charged ions) to form water molecules. During the reaction energy is released, partly in the form of electricity (the electron flow) and partly in the form of heat. In terms of materials, the fuel cell reaction consumes hydrogen and oxygen and releases water. A single fuel cell provides a small amount of power. To meet a realistic demand multiple fuel cells need to be combined in a stack, a connected series of fuel cells. Such a fuel cell stack needs to be integrated into a so-called fuel cell unit, consisting of multiple stacks, circuitry, compressors, sensors, etc."

into more or less centralized in terms of production and distribution (McDowall et al. 2006, 1243), much like the classifications found in chapter 2.2.1.

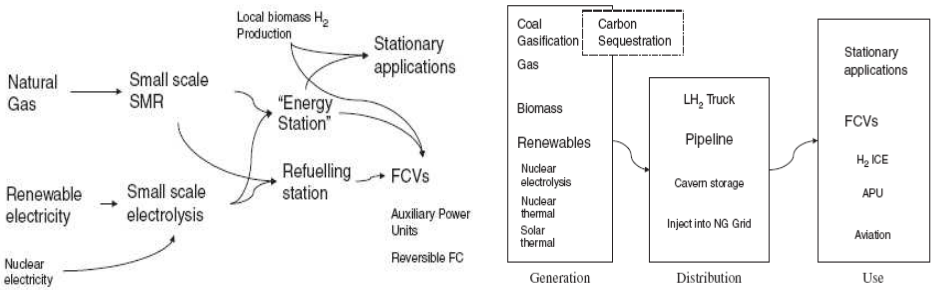
Concerning hydrogen production, one can distinguish between a large-scale, centralized approach and a small-scale and decentralized, local approach. For Wietschel et al. centralized refers to "very big central plants" (2006, 1290) in terms of hydrogen production in contrast to decentral, smaller, more local plants and onsite production at refueling stations. The former has advantages of economic efficiency and the possibility to use all sources and carbon sequestration. The latter has advantages in the area of security of supply and fostering innovation. McDowall and Eames (2006, 1244) similarly identify large-scale steam methane reforming, coal and biomass gasification, renewable electrolysis, nuclear energy, and carbon sequestration as technologies for a centralized infrastructure. They also identify local and small-scale electrolysis using renewables and steam methane reforming of natural gas near refueling stations (onsite production) as technologies suiting a decentralized hydrogen infrastructure. The CeSSA[153] conference in Madrid on hydrogen prospects (14/15-04-2008), finally, differentiated between centralized hydrogen infrastructures that envision large-scale production of hydrogen from mostly fossil fuels through steam methane reforming or gasification with the use of carbon capture and storage technologies (which would be feasible in the short and medium term, but dependent on low hydrogen distribution costs), and decentralized infrastructures that primarily involve carbon-free hydrogen production from local, small-scale solar and wind based electrolysis (which would be feasible in the medium to long term and require the availability of many production facilities / sites).

Concerning distribution, the dividing line is not as simple as it might first appear. Although it is tempting to classify hydrogen gas pipelines as centralized, onsite production as decentralized, and truck distribution as something in between, the classifications of centralized and decentralized distribution are not just about the physical assets involved. The guiding question seems to be whether there exists one integrated national network or that there are multiple regional or local networks separated from each other, but that may ensure nationwide coverage when combined. Wietschel et al. (2006), for example, identify the interconnection between networks as the most important feature of a centralized network. In other words, in how far are local and national networks linked?

Based on these distinctions, McDowall et al. (2006) distinguish between two core hydrogen infrastructures:

[153] CeSSA conference on the 'Prospects for a European Hydrogen Economy'. CeSSA stands for Coordinating Energy Security in Supply Activities.

Figure 6.3 Decentralized and centralized hydrogen infrastructures



Source: McDowall et al. 2006, 1244.

6.2.2 Transitions to Hydrogen

Despite hydrogen's versatility, there exists substantial consensus on the transition process among scientists and policy makers.[154] Hydrogen production would appear to move from onsite and small-scale SMR of natural gas and local electrolysis to more centralized large-scale facilities with a more diverse set of sources ranging from oil and gas (SMR with CCS), coal and biomass (gasification with CCS) to various renewables and alternatives (hydro, solar, wind, and nuclear). Moreover, in this process fossil fuel sources will eventually be replaced by renewable sources. Hydrogen storage and distribution follows a similar path from a decentralized to a more centralized network. Whereas in the beginning onsite production and tanker trucks carrying liquid hydrogen are the main means of distribution, later, when demand is sufficient, pipelines are expected to eventually replace trucks as the main means in especially urban areas. Finally, hydrogen conversion and end-use are also expected to shift from hydrogen internal combustion engines to hybrids and fuel cell vehicles. Advanced ICE will dominate the scene until at least 2020-2030, after which hybrids and fuel cells are expected to become competitive and emerge as mature technologies for mass production. See also Figure 6.4 below. In essence, hydrogen will grow from a local, decentralized or distributed infrastructure into a national, centralized, and interconnected infrastructure.

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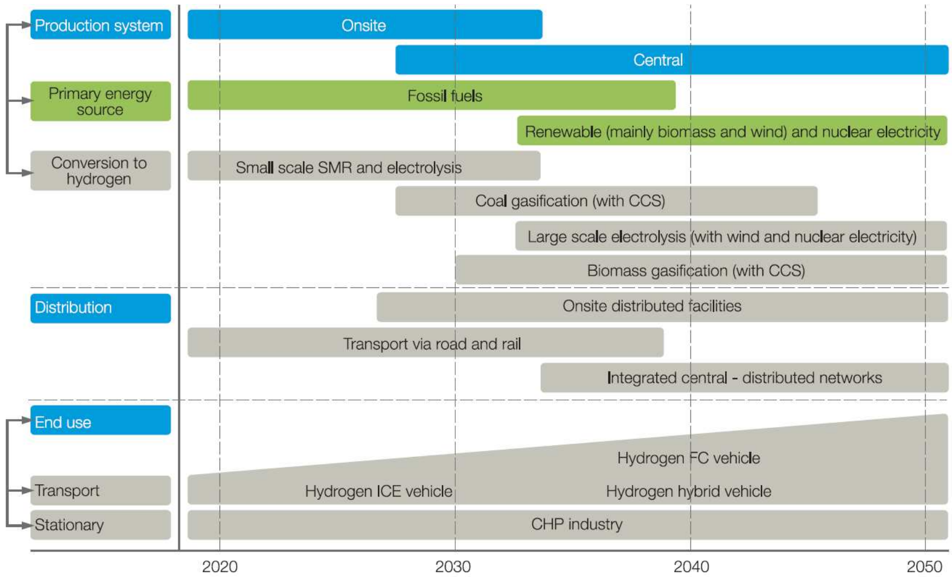
[154] This section is a culmination of hydrogen transition perspectives: Lovins 2003; McDowall and Eames 2006; Müller-Langer et al. 2007; Dunn 2002; Tzimas 2006; Zhao and Melaina 2006; Mulder et al. 2007; Contaldi et al. 2008; US DOE 2008; Adamson 2003, 2005; Ball et al. 2006; Muradov and Veziroglu 2005; Bento 2008; Bleischwitz et al. 2010; Mourik 2005; European Commission 2003, 2007a, 2007b; Bruggink 2009; Ogden 1999; Oi and Wada 2004; Pastowski and Grube 2010; Qadrdan et al. 2008; Ros et al. 2007; Schenk et al. 2007; Hisschemöller et al. 2007; Kok 2004; Uyterlinde et al. 2007; EZ 2005; EREC 2010; ECF 2010; Clark and Rifkin 2006; Solomon and Banerjee 2006; Madsen and Andersen 2010.

Figure 6.4 Speculative timetable for commercialization of hydrogen and fuel cells



Source: Roads2hycom 2007, 35.

Regarding the introduction of FCVs, we already saw that hydrogen demonstration projects are currently testing various prototypes of hydrogen and fuel cell vehicle applications in fleets of buses and industrial vehicles. It is hypothesized that the build-up of FCVs will start from exactly such local, small fleet clusters in urban areas that are dedicated to a central hydrogen depot, which uses current excess capacity and local means, e.g. decentralized and cheap, small-scale natural gas reformers. The serial production of hydrogen FCVs is, however, expected to start only after 2020, when these technologies slowly become competitive. Hydrogen then builds up a market segment in buildings and vehicles nearby these fleet clusters. Hydrogen is likely to be supplied by onsite production facilities (that are expected to emerge around 2020) and through tanker trucks that deliver to refuelling depots and fuel stations that specifically serve small fleet clusters. These so-called early hydrogen user centers then grow in size, number, and geographic overlap, building out of regional corridors. Around 2030-2040, FCVs are expected to achieve a substantial market penetration and evolve into a mass-market product in which fuel cell-driven vehicles will be dominant in transport. To support the introduction of FCVs, a hydrogen network and production facilities need to co-develop that can cope with the growth in demand. In this process, pipelines play the key role as they start to connect the local grids to each other, form the backbone of a national hydrogen network that eventually supplies most fuel stations, and warrant centralized production. Truly integrated central networks are, however, only expected to emerge around 2040-2050, around the same time that mature technologies for the mass-production of FCVs are available. With expansion, improved performance, and cost reduction will come a growing consumer acceptance and home refueling.[155] According to the EU, distributed power generation will remain an important factor in the hydrogen production landscape, even though central production will eventually be the main means.

6.3 Hydrogen Development and Deployment in the Netherlands

This research takes the EU HyWays project, carried out by the Energy research Center of the Netherlands (ECN)[156], as the guideline for modelling the technical characteristics of hydrogen infrastructures at various stages of a transition in the Netherlands. Based on certain assumptions and Dutch energy sector characteristics[157], the EU HyWays project, presents "a bottom-up approach to develop a pathway towards hydrogen energy systems" (HyWays 2007, 7) that takes account of the predicted development of hydrogen demand.[158] The transition to a hydrogen economy, entailing the production, storage and distribution, and use of hydrogen as an energy carrier for personal transportation in the Netherlands is estimated to take place from now until at least 2050. We intend to follow the HyWays roadmap to construct the case of a transition to hydrogen and differ only

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[155] Some important requirements for success are considered to be that vehicles, fuel, and fuel cells develop together, there exist competitive system costs (H2 and FC), high reliability of fueling, onsite fueling with offsite / fast fill capacity, and easy low cost expansion beyond demonstration.

[156] This resulted in a number of publications and presentations by ECN staff on the uptake of hydrogen in the Netherlands such as the paper presented by De Groot et al. (2005), the 2007 Smit et al. article, and the ECN 2010 presentation.

[157] Strong determinants for the hydrogen introduction path are according to HyWays 2007 and de Groot et al. 2005: 1) the industrial hydrogen present in the Rijnmond area; 2) the extensive natural gas grid and the large share of natural gas in the national energy mix; 3) the strong logistics and transport capabilities (for import of feedstocks like coal and biomass); 4) the promotion policies for off-shore wind energy; 5) the availability of huge carbon storage locations; and 6) the population and transport density.

As such it is predicted that: 1) the introduction of hydrogen begins with onsite reforming based on natural gas; 2) natural gas will play a dominant role until at least 2030; 3) SMR capacity in Rotterdam area will produce additional hydrogen; 4) in time large-scale production with CCS and renewable hydrogen is needed; 5) hydrogen production is cost-competitive early on, but fuel cells only later; 6) hydrogen infrastructure seems to become economically viable in 2022 for the Netherlands; and 7) pipelines will grow from the existing industrial pipeline infrastructure.

Some important underlying assumptions are: 1) the cost-margin between large-scale and small-scale hydrogen production is a driver of infrastructure (pipeline or truck) development; 2) the model is strongly region and time dependent; 3) a decrease of fuel cell cost is a very sensitive parameter for the development of hydrogen demand.

[158] Smit et al. (2006) write that the main applications of hydrogen will be the transportation sector and less the residential and commercial sector (CHP). Although this does not exclude stationary applications from their model, as with the HyWays project, it does follow the trend that mobile applications are the main aim. Of course, as we leave out stationary applications, the synergy that might emerge from both developing simultaneously is lost. Hence, the introduction of hydrogen is progressing a bit slower than in the article.

with regard to the timing of the various steps or phases of such a transition. Whereas the HyWays study focuses on 2010, 2020-2030, and 2050 onward, this research focuses on 2020, 2035, and 2050. It does so for two reasons. First, considering the framework of alignment we need clear snapshots of moments in time; phases like 2020-2030 are conceptually difficult because a network might change considerably during this period. This creates problems in identifying the unit of analysis. Second, the ECN studies foresee a later introduction of hydrogen while the trajectory remains largely the same.

What makes the HyWays roadmap so useful for this research is its relative clarity as to which hydrogen technologies and networks will be developed when during infrastructure development. The HySociety project of the European Union, for example, identifies forty-two different hydrogen supply chains out of which Wietschel et al. (2006, 1288-1290) identify ten economically most likely ones for the EU-25. The EU's HyWays project, in contrast, identifies six possible hydrogen supply chains for mobile applications that are more attuned to the Dutch energy sector specificities (De Groot et al. 2005): see Table 6.1 below.[159] Moreover, this list of possible hydrogen infrastructures is narrowed down further when put in a temporal perspective, as we will see below. For now, it suffices to state that there exist three main hydrogen supply chains based on the characteristics of their networks: one based on onsite production, one based on liquid hydrogen distributed by tanker trucks, and one based on hydrogen gas pipelines.

[159] The six supply chains presented in Table 6.1 can be classified in terms of their degree of centralization. The first onsite production based infrastructure would then be decentral for both production and transport. The second, fourth, and sixth would be centralized for both production (only few large-scale facilities for natural gas, coal, and offshore wind) and transport (national pipeline system). The third and fifth would fall somewhere in between. Biomass has the opportunity to be developed in both a centralized and decentralized fashion, though transport is pipeline based. Liquefying hydrogen that was produced centrally from gas, in contrast, makes transport decentral in nature because truck distribution does not entail an interconnected network.

Table 6.1 Dutch HyWays hydrogen supply chains

Chain	Source	Production	First Conversion	Transport and distribution	Second Conversion	End-use
1	natural gas	onsite SMR	-	-	CGH2	mobile & stat.
2	natural gas	central SMR	-	pipeline	CGH2	mobile & stat.
3	natural gas	central SMR	liquefaction	LH2 truck	LH2	mobile only
4	(hard) coal	gasification + CCS	-	pipeline	CGH2	mobile & stat.
5	biomass	gasification	-	pipeline	CGH2	mobile & stat.
6	offshore wind	central electrolysis	-	pipeline	CGH2	mobile & stat.

Source: Mulder 2005, slide 6 and EU HyWays Member State report 2007, 54.
Legend: LH2 stands for liquid hydrogen; CGH2 stands for compressed hydrogen gas; stat. stands for stationary; SMR stands for steam methane reforming; CCS stands for carbon capture and storage.
Note: Mulder deviates from the HyWays report by mentioning stationary applications.

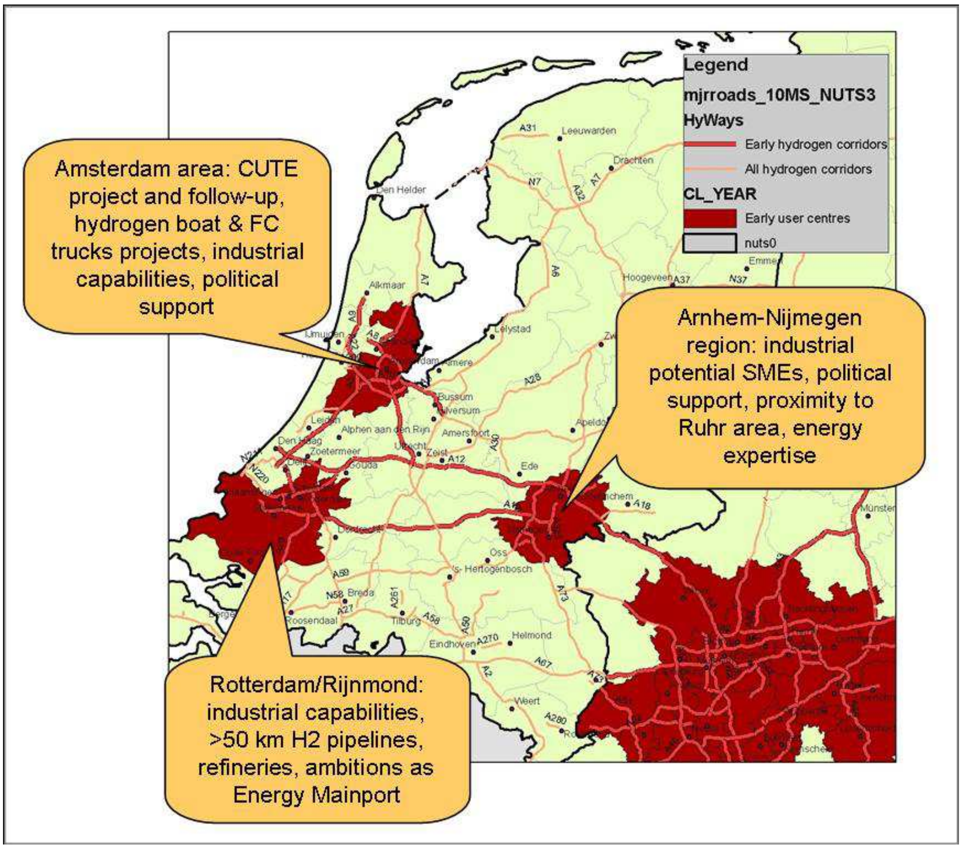
Based on these six supply chains, the HyWays roadmap paints the following picture.

Three core urban areas are planned as early user centers to start up demand: Rotterdam, Amsterdam, and the Arnhem-Nijmegen area. The Dutch introduction of hydrogen is thought to start with niche applications, such as fleets of buses and industrial vehicles involved in demonstration projects.[160] Hydrogen is expected to be used in internal combustion engine vehicles and hybrids first before fuel cell vehicles replace them. Hydrogen is initially produced onsite at refuelling stations in the urban centers through small-scale steam methane reforming of natural gas because of the lack of an existing hydrogen network and the presence of a well-developed gas infrastructure. Other sources are not considered competitive yet. The next filling stations will be erected along the main highways between the user centers and areas adjacent to the user centers along the natural gas network. This will occur mostly in the Randstad, the densely populated urban area in the west of the Netherlands. Tanker trucks are likely to distribute liquid hydrogen to filling stations where onsite production is not possible, i.e. not close to natural gas pipelines. The Rijnmond (Rotterdam) area is considered as the starting point for a national hydrogen pipeline infrastructure due to the existent industrial hydrogen production and pipelines. Hydrogen is produced from additional SMR capacity, meaning that for now, the

[160] Niches identified by SenterNovem are: shipping, navy, consumer electronics, batteries and storage, local hydrogen networks (Rijnmond), emergency power generators, internal transports, industrial vehicles, urban transport, public sector. Larger applications are: shipping construction, transport, energy producers and distribution, consumer electronics, industrial gas producers, filling station build-up.

selling of industrial hydrogen to filling stations is more of a by-product than a core activity. Similar situations are also expected elsewhere. In essence the first and third supply chains of Table 6.1 start the hydrogen transition. Important actors for the success of these first steps are considered to be local and national governments, industrial hydrogen producers and system integrators, and companies with no stake in the current energy infrastructure. Nevertheless, the role of the Dutch natural gas industry cannot be neglected. The local reforming of natural gas into hydrogen and/or adding hydrogen to gas pipelines depends on their network and cooperation.

Figure 6.5 Early hydrogen user centers and corridors in the Netherlands



Source: HyWays 2007, 29.

By 2035, the transition towards hydrogen should be well under way. It is assumed that at this point there is a rapidly growing demand for hydrogen refueling stations in western urban areas and along main roads, because fuel cell cars are now cost-competitive with ICEs and hybrids and are replacing them in terms of market share. Increasing demand also allows for the early user centers to expand into new territories along highways between them and urban areas adjacent to them. New local hydrogen communities may also emerge and be connected to form larger hydrogen user centers.

In response, hydrogen production and distribution are changing rapidly to adjust to the new setting.[161] Concerning production, more efficient large-scale hydrogen production in user centers is replacing onsite facilities. The core production takes place through central, large-scale steam methane reforming of natural gas in Rotterdam (mostly with CCS; the existing central SMR installations will be adapted to CCS). However, central coal gasification (only with CCS), the use of biomass, and to a lesser extent wind energy start to become interesting options due to expected rising gas prices. If the potential of CCS technologies fails to meet expectations or they are still expensive, then more biomass will be used than coal. The emergence of these new sources necessitates new central production facilities and creates new regional hydrogen networks in surrounding urban areas. Concerning distribution, in the urban areas in the west of the Netherlands (Randstad) the beginnings of a centralized pipeline infrastructure for the use of hydrogen as a motor fuel have emerged out of the initially industrial hydrogen pipeline in the Rotterdam area. It will connect Rotterdam to the north with The Hague, Leiden, and Amsterdam, to the south with the first Brabant cities and east with the new hydrogen center of Utrecht. This basically encompasses the Randstad or the key major Dutch urban areas. The Arnhem-Nijmegen user center, however, is still based on local onsite sources and truck distribution. Central SMR plants in Rotterdam "will feed regional pipeline networks which will evolve from the existing industrial pipeline infrastructure or originate from newer plants" (HyWays 2007, 27). However, the growing pipeline network does not only breed new regional pipeline networks, it also incorporates and/or replaces the onsite production and truck distribution network in the western urban centers. In response, onsite production and trucks are found increasingly in rural regions adjacent to urban areas or hydrogen pipelines but where natural gas or biomass is available. Truck distribution now serves as a back-up to and extension of the pipeline network, delivering liquefied hydrogen to those nearby locations just out of reach of the pipeline network.[162] As such, the expanding pipeline and urban networks slowly but surely create the typical long-distance transmission and local distribution networks of infrastructures. However, at this moment in time, it resembles more a set of interconnected subsystems rather than a national grid with local subsystems due to the regionality of the pipeline and the remaining role for onsite facilities and truck delivery. Hence, in 2035, three networks coexist in a dynamic, ever-changing, setting. In this phase the second hydrogen supply chain of Table 6.1 seems to establish itself as the dominant one in the Randstad while the first and third are increasingly phased out or incorporated into the expanding network. The

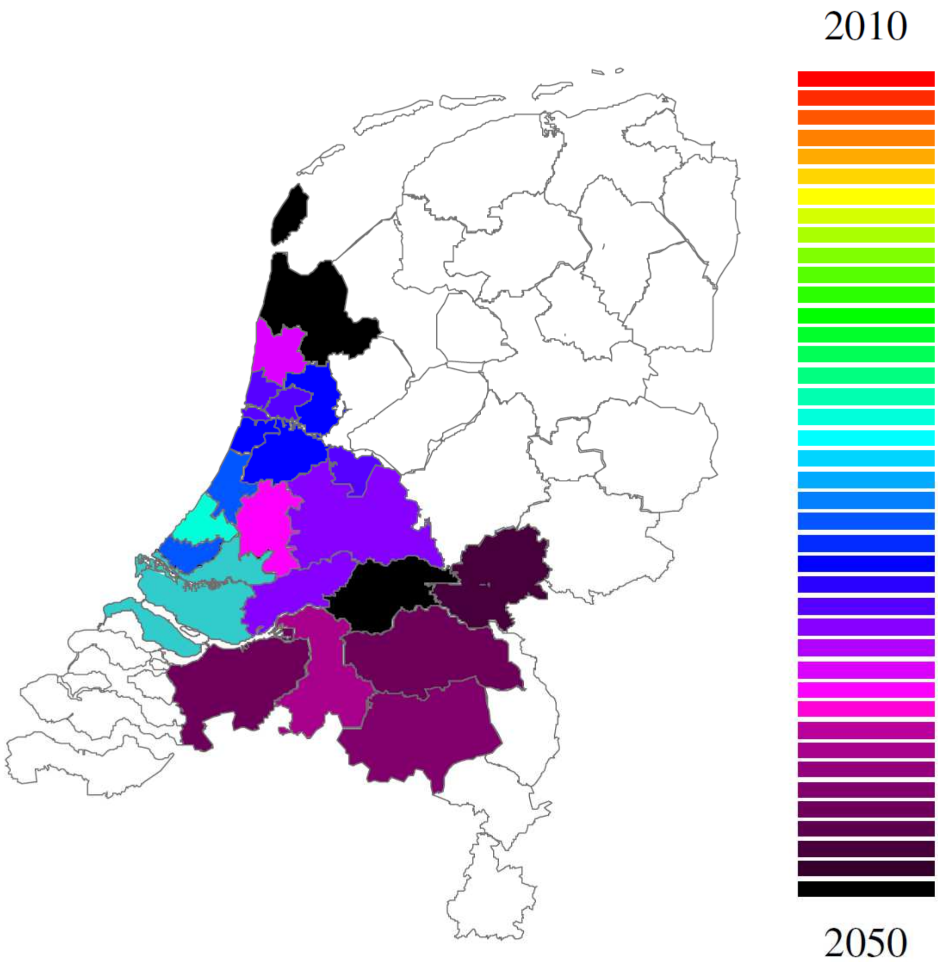
[161] The model shows that local small scale production may generate enough demand to warrant pipelines and large scale production (Smit et al. 2006). The large scale centralized system will evolve when it has lower costs than small scale onsite production. The ECN model estimates also that the cumulative investments will be 11 billion euro, but that a fully developed pipeline system would be between 12 and 20 billion euro.

[162] As long as costs are the deciding factor, connecting remote regions as well as otherwise independent and self-sufficient regional networks remain risky investments. Hence central coordination may play an important role in ensuring complementarity between the expanding national pipeline network and other hydrogen networks.

first and third still remain dominant in the Arnhem-Nijmegen center though. The fourth, fifth, and sixth chain play only a marginal role. A big issue for operations will be the simultaneous development and deployment of production facilities, pipeline networks, and fuel cell vehicles in this dynamic setting. Hence, capacity is sometimes too large and sometimes too small for the market. In cases where hydrogen supply exceeds demand, the natural gas grid functions as an overflow area of hydrogen. This would also fit the greening of gas project of the Dutch government.

By 2050, based on the HyWays hypotheses regarding hydrogen penetration rates, hydrogen will be available throughout the country, with the main user base in the Randstad. Smaller centers are Arnhem-Nijmegen, the Brabant towns, Enschede-Hengelo, Maastricht, and Groningen. The penetration of cars running on hydrogen is expected to be 40% by 2050. Fuel cell vehicles are believed to be the only vehicles in production and will thus eventually replace internal combustion engine vehicles. Heavy trucks may still drive on biofuels though. The widespread use of hydrogen will justify and be possible because of the construction of a national pipeline grid. "This grid will have grown over the decades by integration of regional pipelines that link up decentralized production plants and fuel stations" (HyWays 2007, 28). Based on penetration rates of Smit et al. (2007, 1395), it is expected that a connected hydrogen pipeline system will be in place in 20 to 25 of the 40 regions distinguished in the study, covering most of the urban areas of the Netherlands. Hence, distribution would be done through a pipeline system much in the same way as natural gas is done today, although tanker trucks will also be used to deliver liquefied hydrogen in remote regions where hydrogen demand does not justify the building of pipelines. Hence some coexistence of pipelines and trucks remains. Onsite hydrogen production will also exist marginally in local remote areas further away from hydrogen pipelines where demand is small. Sources for these onsite production plants will be local renewables rather than the natural gas of earlier stages. It is also hypothesized that the centralized pipeline spreading out from Rotterdam might be connected to Antwerp, while the German Ruhr area will extend itself to the Arnhem-Nijmegen area. Hydrogen is produced centrally and on a large scale through the gasification of coal and steam methane reforming of natural gas, with the use of carbon capture and storage technologies. Production takes place near the location of the sources, although the existing natural gas pipelines are likely to favour refining natural gas into hydrogen in Rotterdam, due to the already existing generation plants there. In this situation it is hypothesized that oil has peaked and coal has replaced natural gas as the main source while the need for renewables steadily increases the share of biomass and wind in the energy mix. Hydrogen from renewable sources (wind) is estimated to only take off when pipelines are in place and its costs are comparable to hydrogen from coal and gas. Hence a substantive share of hydrogen from renewables is expected only by the end of the 21st century. By then, hydrogen may also be imported from Norway, Iceland, or North-Africa. The role of wind based hydrogen is thus likely to function more as a balancer in 2050 than as a renewable source. When too much electricity is produced from wind power for the electricity grid it can be transformed into hydrogen. Hydrogen and electricity make up the energy carriers powering vehicles and homes respectively as there are no breakthroughs expected in electricity storage. In the end, the second hydrogen supply chain of Table 6.1 loses its dominance, while the fourth, fifth, and sixth chain start to play an increasingly larger role. Chains one and three still remain in remote, less populated areas. Key is, however, that in 2050 all of these chains are connected through one central hydrogen pipeline network whose growing number of entry and exit points is increasing its operational complexity.

Figure 6.6 Growth of a hydrogen pipeline infrastructure



Source: Smit et al. 2007, 1394.

Although the roadmap presented above represents the prominent perception of a transition to hydrogen as a motor fuel in the Netherlands, there is of course no assurance that things will work out this way. Considering the network as the most important element of an infrastructure – because it ensures the complementarity of the various parts of the supply chain – three main networks were distinguished: onsite, trucks, and pipelines. These three were all present in the roadmap, albeit in varying degrees as time progressed. The general roadmap moved from a decentralized start to a more centralized ending. This immediately allows two basic alternatives to the roadmap to be derived that are in line with the main assumptions behind the roadmap. First is the possibility that when a national central pipeline system is the perceived end-state, why not start building it immediately, skipping the decentralized phase of onsite production and truck distribution? Obviously this is a very risky path. While the diffusion of hydrogen as a motor fuel would likely quicken (perhaps even beyond demand) and the centralized network achieved sooner, government intervention, investments, and assurances would need to be increased strongly. Pitfalls are to be sought in those similar to a strategy of 'picking winners'. Second is the possibility that technologies purposefully follow or get locked into a decentralized trajectory so that the hydrogen infrastructure might remain regionalized in 2050. This follows a path where government intervention is neither required nor desired and the uptake of hydrogen would move at a slower pace following a market demand that is free from political stimuli. However, this route runs the risk that the goal of sustainability is likely to be addressed too little, too late. Pitfalls here are similar to those of a strategy of 'keeping options open'. Although modeling these possibilities would be beside the point of this research, as the illustration of the framework for alignment is served by the main roadmap alone, it is nevertheless important to keep in mind that governments are likely to develop multiple scenarios and investigate several hydrogen roadmaps in real life policy formulation before carrying out their preferred option.

6.4 Conclusion

This chapter introduced the case of a transition to hydrogen. What makes hydrogen interesting with an eye to sustainability is its possible contribution to CO2 reduction and urban air pollution. Since hydrogen leaves only water vapor as an exhaust, can be created by renewable sources, and has the possibility to capture all emissions during its production process if produced by fossil fuels, it creates the opportunity for sustainable mobility. Moreover, its versatility in terms of possible sources and distribution means also creates opportunities for supply security, as one can switch easily from one to another. Drawbacks were found to be the costly and immature nature of some hydrogen technologies and the chicken and egg problem in deployment. The latter was exacerbated by the lack of an automobile industry, which limits the amount of control the Dutch government has over the execution of such a roadmap. Consensus around the PEMFC for FCVs and EU wide coordination might help Dutch policy makers set up agreements with the relevant actors in this regard in order to effectively plan and execute a transition.

The chapter showed that hydrogen was very versatile in terms of sources and production, transportation and storage, and applications, but that national characteristics (a focus on natural gas and the industrial complex at Rotterdam), the exclusive focus of the roadmap on mobile applications, and the steps of the roadmap (different networks at different times) narrow this diversity down considerably for most of the three snapshots. This helps the use of the case as illustration. Three core networks stand out and were present in various degrees in three stages of the roadmap: onsite hydrogen production, liquid hydrogen trucks, and hydrogen gas pipelines. Next to that the roadmap showed how hydrogen moved from small-scale decentral production in to large-scale central facilities near user centers, from natural gas to coal and biomass to greener resources, from onsite production to hydrogen gas pipelines, and from trucks in urban areas to trucks in suburban and remote regions. Overall, the transition centers on the increasing interconnection of local networks and early user centers through the building of a national hydrogen pipeline network. With the technical side of a transition to an infrastructure for the use of hydrogen as a motor fuel in the Netherlands established, it is time to illustrate the application of the framework for alignment on it. How should the different networks be organized for reliability? This will be done in the next chapter.

7. Towards an Organizational Hydrogen Roadmap

In the previous chapter we identified the technical characteristics of hydrogen infrastructures at different stages of development. Let us now investigate what the framework would generate as complementary organizational structures in light of reliability.[163] This exercise serves two purposes: first, to illustrate the ability of the framework to pinpoint the organizational requirements of future Dutch hydrogen networks at various stages of their development (and hence its relevance); second, to investigate the application of the framework on a future case in order to 'learn by doing' and refine the framework further. To this end, in 7.1, the four steps distinguished in chapter 4 are executed for the three hydrogen snapshots. Afterwards, section 7.2 summarizes the findings, creating an organizational roadmap, and reflects on the experiences made during the application.

7.1 Organizing Hydrogen Networks for Reliability

Considering that the technical characteristics of a Dutch hydrogen infrastructure and its development over time were presented in detail in the previous chapter, we can move straight to the application of the stepwise progression. Just a brief recap; the application of the framework centred on the following four steps:

- Identify critical technical functions and accompanying control mechanisms
    - What reliability problems may arise in terms of critical technical functions?
    - How can these be solved? What is required to overcome them?
- Allocate technical functions to supply chain entities
    - Which entities are responsible for the facilitation of the technical functions?
    - How much are these entities involved (one main or all roughly equal)?
- Assessing coordination requirements
    - What is the scope of control and speed of adjustment of the control mechanisms required to facilitate the critical technical functions?
    - How may infrastructure features affect coordination requirements?
- Combine the outcomes of steps 2 and 3 to come to an overall organizational structure
    - To which organizational structure does the combination of entity involvement in and coordination requirements of a specific technical function point?

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[163] Considering that there is no clear organizational structure developed for a hydrogen economy, there is an opportunity to design the hypothetical organizational structure best suited to the technical characteristics of an infrastructure for the use of hydrogen as a motor fuel. Let us reiterate that by making a stepwise progression from technologies to organization, the matching optimal structure is determined by technological characteristics entirely, neglecting all other considerations.

- What organizational structure might encompass all operational requirements?

Before starting the actual application, however, there are two important comments that need to be made at this point.

First, we need to clearly establish at which stage specific hydrogen codes and standards are developed. These control mechanisms were not addressed in the previous chapter, which focused on technical characteristics only; yet the presence or absence of them proved important in chapter 5. As a general rule, it appears that in order for a system to function without interoperability problems at any given moment, the standards applied need to be developed in the period leading up to it. In this light, when hydrogen is used in independent user centers in 2020, hydrogen production / quality and truck delivery standards should already be in place to allow car and fuel cell manufacturers to produce their automobiles and engines accordingly. The same goes for 2035 and 2050. When the local centers are start to interconnect through the growing pipeline network in 2035, central gas, coal, and biomass and hydrogen pipeline standards need to be in place. Finally, by the time we reach 2050, one can safely assume that renewable production standards have been established. As such, the standards necessary to enforce in one phase are part of the planning and development of the earlier phase. We should particularly keep in mind that for the 2020 phase, standards have basically been in the making since 2010.

Second, the hydrogen roadmap shows that whereas in 2020 and 2050 the contours of the hydrogen infrastructure are relatively clear, the co-existence of all three hydrogen networks in 2035 makes the hydrogen infrastructure composed of a rather diverse set of technologies. We already saw with the electricity, natural gas, and petrol infrastructures in the Netherlands that truck delivery and pipelines require rather different coordination; and now onsite production is also added to them. The question arises as to whether the framework is able to deal with such diversity considering its focus on one network at a time so far. If so, then there is no problem. If not, there are basically two ways to proceed. First, we can deal with each of them separately and then integrate them. Second, we can focus on the main network and treat the others as additional to it. In the end, the application below does both.

7.1.1 2020; Independent Local Hydrogen Centers

In the endeavour to identify the critical technical functions and organizational structure for 2020, the snapshot of three independent user centers based on small-scale, local onsite production from natural gas supported by truck delivery (after liquefaction) needs to be remembered. Moreover, these simplistic hydrogen infrastructures existed in an emerging, but slow-changing environment.

7.1.1.1 Critical Technical Functions and Control Mechanisms

Interoperability knows three main issues in this early stage. First of all, the content of hydrogen gas, produced onsite or central in Rotterdam from natural gas, and the specifications of fuel cells in vehicles must be attuned to each other in order to ensure the successful uptake of hydrogen as a motor fuel on the one hand and fuel cell efficiency and durability on the other. Hydrogen based cars should be able to refuel at any filling station in any of the early user centers in order to be attractive as a fuel for personal transportation. The quality or purity of hydrogen depends on its sources and production method. Just as the exact compounds of natural gas from different sites differ, so too may hydrogen gas differ if produced from natural gas, coal or biomass, let alone the purity achieved by electrolysis. In addition, fuel cells come in different shapes and sizes. An agreement between car manufacturers and hydrogen producers needs to be reached. Second, hydrogen industrial pipelines and liquefied hydrogen trucks need to be able to handle hydrogen's properties, i.e. to avoid the embrittlement that would occur if natural gas pipelines are used or to limit the boil-off that would take place if no special tanks are used. Although not a problem at short range, problems of boil-off need to be addressed for longer distance truck distribution. In addition, storage means also should match hydrogen's inherent characteristics. The standards for these issues should have been set up in the period leading up to 2020 and are now in need of compliance and/or enforcement.[164] Finally, an eye needs to be kept on foreseeable developments that could change the existing technology, since a core set of dominant technologies is still forming. We saw that the roadmap contains shifts in hydrogen sources from natural gas to coal and biomass, from local to central production, and from truck to pipeline distribution. The pipelines in particular will require specific hydrogen standards and clearly defined access conditions, since it functions as the centerpiece of the infrastructure. Another matter that needs to be kept an eye on is avoiding the development of divergent preferences and norms. The Dutch roadmap harbours special risks in this regard because of the technical independence of the early user centers. The local networks each have their own onsite production facilities, truck distribution systems, and filling stations. This implies some form of collective development of standards.

In 2020, interconnection is somewhat of an issue. On the one hand, the various early-user centers operate independently from each other because they are not physically connected. On the other hand, within the three core centers, there are linkages between onsite production facilities and the truck distribution to fuel stations located further away from gas distribution networks. This step necessitates the liquefaction of hydrogen gas into a dense liquid according to the roadmap, although hydrogen may alternatively be transported in gas cylinders. This will require some facilitation. In addition, there is a connection between hydrogen onsite facilities and the networks of hydrogen sources. Onsite production can only take place near natural gas pipelines or petrochemical sites where hydrogen features as a feedstock.

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[164] To a certain extent these already exist in the form of hydrogen's industrial standards or agreements for demonstration projects. What may help to come to a standard in this regard is that hydrogen is initially produced solely from natural gas, although one needs to be aware that the standard set may also predetermine standards for alternative hydrogen sources in the future. For the Netherlands, a problem is the lack of domestic car manufacturers. As such, the standard setting of fuel cells by the major global car manufacturers and EU norms and standards need to be taken into account and is likely to require regular consultations and meetings among the involved parties.

Moreover, onsite production is not possible everywhere along natural gas pipelines, simply because many locations do not have the space required for a sizeable reformer. Yet, one may argue that onsite production is not truly a hydrogen network, considering it is technically the natural gas pipelines that are being used. Then again, if national hydrogen coverage would be ensured by onsite facilities, we would still call it an infrastructure, albeit a highly decentral one. Next to facilitation, planning for future interconnectivity is required since all local centers will at some point be connected to form a national hydrogen network. This raises some questions. Where should, for example, the national pipeline be located to best serve the local networks of user centers? Where should urban pipelines be located to replace onsite production and truck distribution networks in user centers? In this light, consideration also needs to go to the locations of production facilities and filling stations; what are good spots now and later?

Capacity management seems to be a very minor issue at the outset for hydrogen. Onsite production makes capacity management issues home to the natural gas network rather than the hydrogen network as such. Operational balancing simply does not exist when there is no integrated hydrogen network. Quite the opposite: hydrogen could provide an additional storage medium at the onsite production facilities to alleviate the balancing of the natural gas network. Depending on whether natural gas is required or needs to be stored, hydrogen can be produced and fed back into the pipeline to a certain degree. In addition, truck delivery should not pose more difficulties for management than the distribution of petrol is causing today. There are no flows to direct in real time. However, there might be the need to check hydrogen compounds at onsite production facilities (that also serve as storage depots and liquefaction facilities) before distributing the hydrogen. Hydrogen truck delivery involves a very loosely coupled network that is very flexible in the sense that the malfunctioning of one truck is easily remedied by its replacement by another; there are no cascading effects. Even the malfunctioning of an onsite production facility or the occasional occurrence of a sold-out filling station does not automatically result in a critical technical failure. There remain plenty of other facilities and fuel stations one could drive to. Moreover, some additional trucks might be used to supply an onsite facility during reparations or fuel station on short notice. In other words, because of the lack of continuous flows through an interdependent network, there are no matters of operational real-time balancing that need addressing. Next to that, the hydrogen pipeline used in Rotterdam is essentially an industrial process. Hydrogen is used as a feedstock and distributing it to fuel stations is only its secondary use. As such, it cannot be called a network in the way we would describe the current natural gas network. Concerning tactical management, there is only a very limited need for unit commitment and maintenance scheduling. On the one hand, onsite facilities can decide for themselves when and how much to produce and may execute maintenance at any time when they have stored sufficient hydrogen for consumers to use in the meantime. On the other hand, truck companies that deliver hydrogen from production sites to fuel stations do need to commit trucks for delivery and need to take maintenance into account. Of course, any shortage is easily remedied by adding a few spare trucks. Strategic management is another aspect of capacity management that has some minor issues to be dealt with. The location of future central and onsite production facilities, truck depots and liquefaction sites[165], and pipelines should be considered in light of infrastructure development as depicted in the roadmap, just as the focus on natural gas should be considered against the possibility of other future sources.

System management concerns foremost the overall coordination of hydrogen demand and supply. Considering the local nature of demand and supply and the small amounts involved in the early user centers, few problems are to be expected, especially as natural gas supplies are ensured by domestic production. Action is only required when demand outgrows or stays behind the capacity of onsite production facilities or truck delivery. If so, additional onsite production facilities, extra delivery trucks, and truck delivery from other facilities and user centers might prove a solution while the presence or absence of subsidies and taxes might help manage demand for hydrogen based vehicles. Storage at onsite facilities also helps to maintain operations in case of malfunctioning onsite production. Together with the flexibility of trucks there are plenty of ways to handle system management. Regarding the quality of service, affordability, availability, and increasingly sustainability have to be balanced.[166] As one of the main reasons to switch to hydrogen is to reduce CO2 emissions, production from renewable sources (electrolysis) might be preferable to that of natural gas, especially since CCS technologies are not likely to be in place by 2020. However, if hydrogen is to be a commercially competitive technical possibility, natural gas reforming seems to be the only viable option in the short run. According to the roadmap, it seems that costs are the main criteria at this stage, as starting demand with natural gas takes preference, while sustainability seems to be a longer-term goal. Consequently, natural gas based hydrogen can be considered to be affordable in 2020 and sustainability a matter for later. Hence the only issue in need of addressing in 2020 seems to be the availability of hydrogen. Fuel stations might not be equally well represented in the user centers, simply because not all locations are equally lucrative for business. Yet for the uptake of hydrogen and the quality of service for customers, hydrogen should be as accessible as possible.

7.1.1.2 Allocating Technical Functions

The entities responsible for facilitating the critical technical functions depend on whether one looks at onsite production or truck delivery. For purely onsite production based hydrogen 'infrastructures', the entities of production, retail, and storage / liquefaction are one and the same; no network exists. In this light only four

[165] Such depots and liquefaction sites are most likely to function as the interconnection between natural gas pipelines and truck distribution. In early stages, this would be the onsite facilities. Later these may be placed near more rural 'ends' of the natural gas networks so that any truck delivery is short-distance in nature.

[166] Reliability is normally one of these performance criteria. Yet because this research takes reliability as its core objective, it does not feature here. However, taking reliability as the overall objective does not mean that consumers simply forsake the trade-offs among availability, affordability, and sustainability. It merely implies that the desired trade-off needs to be ensured in a reliable fashion.

actors are involved, the producer-retailer, the source, the consumer, and the regulator. Regarding technical functions, we need to remember that there are no interconnection and capacity management issues for this onsite hydrogen infrastructure. In this configuration, both the development and upholding of codes and standards (interoperability) are the responsibility of the regulator and the producer-retailers. While the regulator plays a key role in mediating between the various onsite producers in setting up standards, the various onsite facilities each carry the main responsibility for complying with them, while the regulator may need to enforce them. Concerning system management, onsite facilities are the sole responsible executive entity whereas consumers affect demand and the entity sources (the natural gas infrastructure) affects supply. The regulator influences operations through universal service obligations. For example, regulators may demand that certain non-profitable locations are served to ensure dense coverage.

For truck delivery of hydrogen from onsite facilities to filling stations further away from the gas network, six actors are involved: one source (natural gas), many onsite producers (plus storage and liquefaction means), a few truck distributors, hundreds of fuel stations / retailers, thousands of consumers, and a single regulator. There, the truck distribution company is not an operator in terms of an integrated network, but much more a regular firm providing a transport service, while the fuel station is only a retailer and not a producer. The three may of course also be integrated into one firm. In that case, the onsite producing branch may utilize the truck distribution branch to deliver hydrogen to its branded fuel stations or even to other fuel stations not owned and operated by the firm. This way, an onsite producer may be able to produce more hydrogen than it can sell at its own site. In the end though, whether different companies or different branches are involved, the technical operation involves the same steps. Let us now allocate the technical functions of this truck based hydrogen infrastructure.

Looking at interoperability, compliance to standards is the direct responsibility of the onsite producer (for hydrogen gas contents, storage means, and liquefaction procedures) and to a lesser extent of the distribution company and fuel stations. The regulator is the key responsible entity for overseeing and enforcing standards in all centers. Establishment is mainly the responsibility of the regulator, although it also directly involves the other three entities during negotiations. The planning and facilitation of interconnection centers around the truck distributor; it is the sole responsible for the delivery from onsite facilities to fuel stations. However, onsite producers play an important supportive role by providing storage capacity and the liquefaction necessary for truck delivery. The operational, tactical, and strategic capacity management formed no critical technical function besides the placement of onsite production facilities (preferably close to future hydrogen sources) and truck delivery unit commitment. In addition, some planning with regard to future central production sites, pipeline locations, and truck depots and liquefaction sites is in order. Unit commitment concerns the truck companies that connect production and retail, while onsite producers are free to choose their locations independently from network concerns. Planning for the future, however, involves onsite producers, truck companies, and retailers alike. Finally, quantity and quality management of the overall system depends on onsite producers for the volume and quality of hydrogen gas (strong direct involvement), fuel stations for providing the quantity demanded (weak direct involvement), and the role truck distribution plays in matching demand and supply (strong direct involvement). A regulatory body ensuring delivery of hydrogen to uncompetitive fuel stations might be required so that availability (the quality of service) is ensured. Of course, consumer behaviour influences demand patterns, as do developments in the natural gas network. The allocation is summarized in Table 7.1 below.

Table 7.1 Contribution of entities per technical function in 2020

Entities	Amount	Inter-operability	Inter-connection	Capacity Management	System Management
Sources	One	--	--	--	-
Onsite production, storage, and liquefaction	Many	+	-/+	+/-	+
Trade	None	--	--	--	--
Transmission	None	--	--	--	--
Storage	None	--	--	--	--
Truck distribution	Few	+/-	+	+	+
Metering	None	--	--	--	--
Retail / fuel stations	Hundreds	+/-	--	+/-	+/-
Consumption	Thousands	--	--	--	-
Regulation	One	+	--	--	-/+

Legend: 6 degrees of involvement are distinguished from least to most:

--	No involvement.
-	Indirect involvement (entity affects operation or planning).
-/+	Supportive involvement (set ramifications, data providers, oversight).
+/-	Weak direct involvement in daily operations (entities involved in operations).
+	Strong direct involvement (key operational responsibilities).
++	Leading involvement (central coordinating entity, system operator).

7.1.1.3 Assessing Coordination Requirements

In 2020, interoperability can be considered the most critical technical function. The control mechanisms identified involved the adherence to codes and standards while keeping an eye on future developments that could require new standards. Compliance is especially relevant in this early phase because most standards will have been settled upon only recently (in the years leading up to 2020[167]), making them vulnerable to

[167] As mentioned, it is likely that by 2020 most standards are already in place for hydrogen gas, production methods, distribution means, and fuel cells because they essentially already exist in the form of industrial standards and have been applied in demonstration projects. However, let

reconsideration or continuation of other practices that also emerged. Moreover, the independence of the three early user centers harbors the risk of diverging standards developing over time. Finally, while the dominant design intended by the roadmap (pipelines) might still be many years away, standards need to be clear for early hydrogen applications to develop and function in its light as well. What does this imply in terms of coordination requirements? Regarding the scope of control involved for upholding standards, interoperability concerns both the component and system levels. On the one hand, standards are upheld by entities themselves and it is generally in their self-interest to comply in order not to lose customers. For example, onsite hydrogen producers can only sell hydrogen if it matches fuel cell standards and truck distribution is less efficient if boil-off occurs. On the other hand, interoperability has a systemic character in that fuel cell vehicles should be able to travel between the various independent hydrogen centers, i.e. consumers need to be able to refuel in any of them to ensure mobility. Thus while standards apply to components, they have systemic repercussions. This implies the need for a central entity, likely a regulator, supervising compliance to standards nationwide. The scope for planning developments involves the system, considering that it involves setting system-wide standards. Regarding the speed of adjustment, complying with standards is a matter of the short term. This is because monitoring needs to occur continuously and actions might need to be undertaken quickly regarding hydrogen production and truck delivery. However, direct supervision in the immediate term is only required for a tightly interconnected network (as we saw with natural gas and electricity), because a failure in those affects the whole infrastructure while failure in an onsite facility or truck need not be too catastrophic for the entire infrastructure. Planning obviously involves the long term due to the negotiations required to establish standards. Interoperability is hence both a short-term component level issue regarding the compliance with codes and standards with some added systemic checks on the one hand and a long-term systemic issue involving the careful planning regarding future developments on the other. According to Figure 4.2 this would lead to modes of organization of 'self-monitoring and voluntary adjustment' assisted by regulatory 'compulsory monitoring and enforced adjustment' and 'directive planning' respectively. This leads to a very mixed bag of criticality. Whereas regulatory oversight would be regarded as very highly critical, the other aspects would imply medium and low criticality respectively. Two comments in this regard. First, regulators check the actions of entities; they do not direct their actions in the operational real-time sense. Hence the mode of organization stated above is somewhat misleading. Second, it remains to be seen for how long regulatory oversight is required; while setting standards might involve urgent action among many entities, but once established and accepted, voluntary adjustment will replace the need for continuous coordination in this regard. Let us therefore consider the coordination requirements of interoperability to be of high criticality and require continuous coordination among key entities at this point in time.

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us also restate that it is useful to treat these as if they still need to be created in order not to ignore these matters. To fit the development of standards into the roadmap, it should take place before 2020 and come to a close around that time.

Regarding interconnectivity, facilitating the current linkages between a) natural gas networks and onsite production and b) onsite facilities, truck distribution, and fuel stations on the one hand, and the planning for and development of future interconnection of early user centers on the other, create some minor necessity for coordination. Considering that facilitation takes place within either the onsite facility or the local hydrogen center (for truck distribution), it involves the component or subsystem scope of control respectively; and because both onsite production and truck delivery do not have the stringent conditions of pipelines (they represent a network based on non-integrated components), it involves the short-term speed of adjustment. This leads to modes of organization of 'self-monitoring and voluntary adjustment' (onsite) and 'mutual monitoring and stimulated adjustment' (trucks). The planning of future connections, most notably regarding the roadmap's expanding national pipeline network and the building of future urban pipeline networks, involves the long term and the system and subsystem scope respectively. The complementary modes of organization would then be 'directive and indicative planning'. Although this addresses the critical technical function of interconnectivity as defined by Künneke et al., we would like to consider the development of new network connections as a separate activity or aspect of interconnectivity. There is a difference between planning, development, and facilitation. Whereas planning is a long-term matter, at some point the outcome needs to be transferred into action (development or allocation of new capacity), only after which facilitation is required. This differs, for example, from interoperability where the development of standards does not require a period of physical asset development. In this sense development takes place in the medium term, in between planning and facilitation. For 2020, the scope involved is the subsystem considering development in 2020 concerns the development of trucks (capacity) and onsite facilities. This leads to a mode of organization of a 'guided allocation mechanism'. Focusing on the facilitation of interconnection, the coordination requirements sit between low and medium criticality, requiring voluntary adjustment by onsite producers and somewhere between voluntary adjustment and common operation for truck distributors. On the one hand truck companies are the sole responsible for interconnection and need not coordinate with onsite producers and retailers for managing the truck network. On the other hand, in this early formative stage it might be prudent to coordinate the building of the emergent hydrogen network. In the end though, interconnection is only an issue of low criticality at this stage from a national perspective, considering the three independent early user centers.

Capacity management is a bit of a non-issue in 2020. Real-time operational balancing is not required, as no hydrogen network exists in the case of onsite production and industrial hydrogen and the use of liquid hydrogen trucks does not involve an integrated network. The risks and consequences of failures are also lower because the hydrogen user centers operate independently, the use of hydrogen trucks creates flexibility, and hydrogen storage in depots at onsite facilities (or in trucks) is possible. Tactical management in turn requires some minor attention to unit commitment and maintenance by truck companies; it is no issue for onsite generation. Though unit commitment and maintenance are the sole executive responsibility of the truck distribution company, it does require some coordination with onsite producers and retailers in the form of contracting of capacity. Considering that delivery takes place in the user center, it involves the subsystem scope. Action for unit commitment and maintenance scheduling is required in the short- to medium-term for the execution and drafting of delivery contracts respectively. It may be expected however that these activities pose few technical challenges due to the simple network set-up: one source (natural gas), local production facilities (small-scale onsite reforming), non-integrated distribution means (trucks) and little demand at filling stations. The mode of organization is somewhere between 'mutual monitoring and stimulated adjustment' and a 'guided allocation mechanism'.[168] Regarding strategic management, some long-term 'directive and indicative planning' concerning new onsite and central production facilities within local user centers (subsystem level) and nationally (system level) seems wise. Moreover, truck distributors should start preparing for infrastructure developments that may alter their role and operational field. All in all though, capacity management should not be a major concern in 2020. The criticality levels matching the modes of organization are set between low and medium criticality for the more immediate and long-term issues respectively. Focusing on the former, it seems that autonomous entities that voluntarily adjust operation to a common goal is sufficient to meet the coordination requirements.

Regarding system management, only minor criticality exists for the balancing of overall demand and supply in this slowly emergent setting due to the small scale and operational simplicity of the networks in this phase. The quantity issue identified can be handled by back-up trucks that might replace broken trucks on short notice and/or deliver hydrogen from other onsite production facilities within a user center or, in more extreme cases of sudden demand increases or local supply shortages, from other user centers. Moreover, a failure in one of the three networks or early user centers does not automatically mean that the others are affected. In addition, in case of a lack of hydrogen at a fuel station, there are plenty of other fuel stations where vehicles can refuel. Finally, the proper allocation of onsite production facilities and back-up deposits also helps. What, then, makes this technical function somewhat critical? It is the scattered nature of responsibilities across entities. No single entity is able to address it alone; instead, it is an effort that involves all relevant entities. The facilitation of system management requires watchfulness and coordination in order to ensure it. Considering early user centers as subsystems and seeing that actions need to be undertaken in the short and medium term, we arrive at the modes of organization of 'mutual monitoring and stimulated adjustment' and 'guided allocation mechanism'. Regarding the availability of hydrogen, a regulator should ensure that less lucrative locations within user centers are served. One cannot expect that producers, truck companies, and retailers move there voluntarily. While this requires some institutional

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[168] It is interesting to note here that while a simple technical set-up may require extensive government intervention from an economic perspective, while a very complex technical system may be left to private actors. Because a simple technical set-up is prone to one supplier and few consumers (filling stations), the government needs to prevent abuse of monopoly power. In a complex technical network, on the contrary, many suppliers and consumers exist, allowing for competition. Of course, this runs counter to the amount of coordination required to deal with the technical complexity and management of the network.

incentives by the regulator, it is not a technical matter as such. In all, the control mechanisms of system management involve medium criticality and require the relevant entities to commonly keep an eye on operations.

Summing up, the overall level of criticality for a hydrogen network in 2020 according to the framework is quite low. This basically stems from the fact that capacity management and interconnectivity can both be largely neglected while system management involves some minor effort. Only interoperability appears to be an important issue; without adhering to standards the network simply will not function at all. The coordination requirements are summarized in Table 7.2 below.

Table 7.2 Coordination requirements of technical functions for hydrogen in 2020

	Interoperability	Interconnection	Capacity management	System management
Coordination requirements	+/-	-	-	-/+

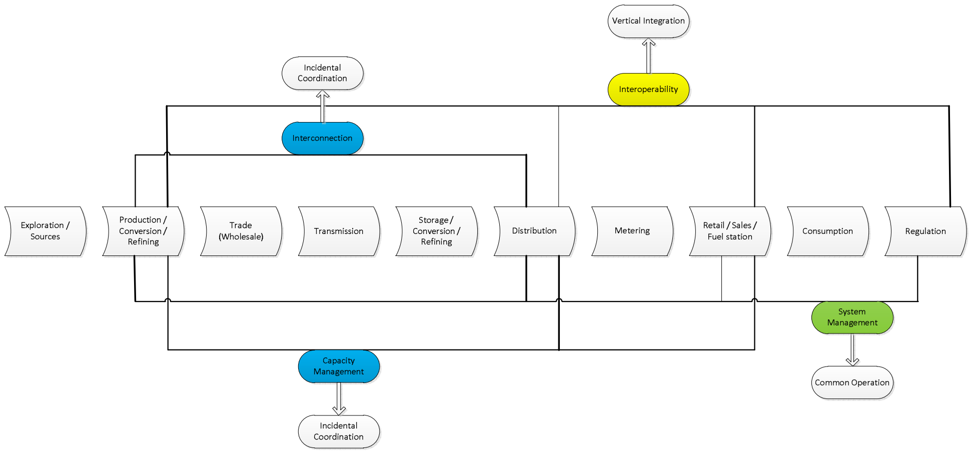
Legend: 6 degrees of criticality / central coordination requirements can be distinguished:

- -	Not critical; autonomous entities act without need for coordination.
-	Low criticality; autonomous entities that voluntarily adjust operation to a common rule/goal.
-/+	Medium criticality; common operation based on agreement between autonomous entities.
+/-	High criticality; continuous coordination between key entities.
+	Very high criticality; central coordinating center that monitors and responds.
++	Most critical; central coordinating center that dictates and supervises.

7.1.1.4 Towards an Organizational Structure for 2020

If we combine the results of steps two and three for the individual critical technical functions, we find that interoperability involves many entities, but that none of them play a leading role, and high criticality, i.e. requires a fair degree of coordination. According to Table 4.2 this urges for vertical integration. Interconnectivity seems to involve only truck distributors and onsite producers and little coordination due to the fact that hydrogen production can be stored and is sold onsite and hydrogen truck delivery involves only the entity distribution. An organizational structure of incidental coordination seems sufficient to address hydrogen transfer agreements which once established may guide further production-delivery operation. Capacity management is largely absent as a concern due to the lack of an integrated network and the possibilities of onsite production and truck delivery. The few entities involved and their local reach require only incidental coordination. Finally, system management involves a multitude of entities (onsite producers, truck companies, retailers, and regulators). Considering the medium level of criticality, common operation would appear to be the suitable organizational structure to coordinate the uptake of hydrogen demand and supply. The result can be seen in Figure 7.1 below.

Figure 7.1 Towards an organizational structure for 2020



Legend: No and indirect involvement = no line
Supportive and weak direct involvement = normal line
Strong direct involvement = bold line
Leading involvement = fat line

Not critical = white
Low criticality = blue
Medium criticality = green
High criticality = yellow
Very high criticality = orange
Most critical = red

Overall, it seems clear that in 2020 the key players are the onsite production facilities and the truck distributors while fuel stations and the regulator play a secondary role in maintaining the technical functioning of the early hydrogen centers. With regard to criticality, it was high for interoperability, medium for system management, and low for interconnection and capacity management. Combined with the small scale and simplicity of the hydrogen networks, a vertically separated form of organization seems adequate. However, it is somewhat unclear whether regular coordination is required. On the one hand, the technical characteristics of the infrastructure do not require much coordination among the entities for daily facilitation. Compliance with standards is component based, for example, and regulatory oversight (enforcement) also does not require much coordination among entities as such. Even hydrogen distribution does not require regular coordination; since hydrogen can be stored at onsite production sites, in depots, and at fuel stations, truck delivery does not have the stringent balancing conditions of pipelines. Each step in the technical process can be performed by a separate entity. It is as if hydrogen is a mere commodity that is not bound by the complementarity commonly present in infrastructures. That does not mean that operation would not be more economically efficient in the case of vertical integration of production, distribution, and retail. It simply means that technically there is no need to fear for reliability. On the other hand, there seems to be a need for regular coordination between entities to tackle the planning and development issues (regarding standards, interconnection, strategic capacity, and system management) that can be expected considering the roadmap. In the end, the most appropriate organizational structure lies somewhere between the structure wherein each entity takes care of its responsibilities in technical operation in a largely autonomous fashion (incidental coordination) and the structure wherein autonomous entities regularly coordinate operations and take common responsibility for the functioning of the infrastructure as a whole (common operation). With exclusive respect to the daily operations of this snapshot, the former seems sufficient. However, with the roadmap in the back of our minds, it might be more prudent to opt for common operation.

7.1.2 2035; An Emerging Hydrogen System

The pathway identified three coexisting hydrogen networks for this snapshot: pipelines, trucks, and onsite production. Although they could all serve to create a functioning hydrogen infrastructure, in our roadmap they exist both next to and connected with each other. The roadmap's picture of 2035 creates a very chaotic picture of hydrogen technologies in place. Discussing all possible combinations is not only very challenging, but likely to be needlessly confusing and long. We propose therefore to focus on two key networks that together manage to capture the core of the infrastructure in 2035; one based on pipelines and trucks in the west and south of the country and one based on onsite production and trucks in the east and north. Considering that the onsite-truck network was already discussed for the 2020 snapshot, and no fundamental changes have occurred in this respect, our attention in the application of the framework on the 2035 below goes to the newly emerging western pipeline-truck network. However, when we address the overall organizational structure in step four, we need to bring the onsite-truck networks back into the picture.

To continue then, we need to remember that the western network around 2035 basically consists of multiple regional networks that are interconnected. The typical structure of a core network and several subsystems has yet to materialize, however, despite the role the expanding Rotterdam pipeline grid is already playing and will be playing in 2050. At the same time, it is very different from the three independent hydrogen centers of the previous snapshot, because the networks themselves now connect the user centers, in contrast to the shared use of hydrogen as a fuel. The 2035 snapshot highlighted as important characteristics the dynamic nature of a hydrogen network, pointing to the rapid growth of hydrogen demand, the growth of centralized large-scale hydrogen production facilities that replace onsite facilities[169], and the expansion of the Rotterdam pipeline network in the Randstad. This in turn changed the role of trucks from transporting hydrogen from onsite facilities to retailers to being a local extension of the pipeline network that transports hydrogen to fuel stations and as back-up capacity in case of emergencies. Important in this pipeline-truck combination is the necessity of liquefaction, which is considered here as a separate entity, coupled to storage or production facilities. As we will see, this strongly affects the organizational requirements of the technical functions.

[169] Onsite producers are unlikely to start feeding hydrogen into the pipeline network because they are deemed to expensive to compete with centrally produced hydrogen.

7.1.2.1 Critical Technical Functions and Control Mechanisms

Regarding interoperability in 2035, hydrogen production standards for central natural gas, biomass and coal, and the specifics for pipelines need to be adhered to. As for their development, it is assumed that they have been set during the decade leading up to this phase. Of course, the other standards for onsite production, trucks, storage and liquefaction, and fuel cells also still need to be taken care of. Especially relevant is the fact that with the pipeline come access conditions for producers and retailers. This makes regulatory control less necessary as entities are now more inclined to comply with standards; otherwise they might not be allowed access to the network and as such cannot be part of the hydrogen market. Next to that, planning in anticipation of market developments, new services and applications, new sources and production methods, and new distribution and storage means remains necessary to ensure future complementarity. For example, hydrogen production from renewable sources and new fuel cell technologies are expected to increase in the decades leading to 2050. These production processes will require their own standards to ensure the quality norm of hydrogen is met. An important difference from 2020 is the fact that the regional pipeline network in the west of the Netherlands presents an emerging dominant design. This invites further standardization around it, limiting the possibilities of future technologies to those that are compatible with the dominant design, if only because of existing agreements with the hydrogen distribution and FCVs industry. Hence these additions are better seen as incremental additions to the emerging dominant design of hydrogen standards.

Interconnection moves to the fore as a most critical issue due to the dynamic setting. Four issues need to be developed and facilitated: 1) the expansion of the regional pipeline network from Rotterdam to the west of the Netherlands (incorporating the Amsterdam center); 2) the simultaneous building of urban pipeline networks that replace local onsite networks; 3) the connection to areas in the vicinity of hydrogen pipelines where liquefied hydrogen remains distributed by tanker trucks; and 4) the linking of hydrogen networks to coal and biomass based hydrogen production facilities and furthering the connection to the natural gas network. These drastically redefine the hydrogen infrastructure. Not only will the pipeline and truck networks coexist in an interconnected fashion (through storage-liquefaction sites), but also will the role of these means continuously change at the same time. For example, as the Rotterdam pipeline network starts to serve the Randstad area, replacing onsite production, and becomes the core of a future national network, trucks will start to serve filling stations further away from the emerging hydrogen and natural gas pipelines, i.e. the niches left by the hydrogen pipeline. As such, trucks increasingly start to operate according to the needs of the pipeline. This necessitates liquefaction at production sites or pipe exits. In this rapidly changing environment coordination is of the utmost importance to ensure that the various hydrogen networks operate in a complementary fashion. The careful planning of the previous phase thus turns into immediate development and facilitation of interconnectivity. However, this does not imply that planning is no longer required. The roadmap towards a central pipeline infrastructure is far from complete. For example, the Arnhem-Nijmegen user center still falls outside the scope of the pipeline system and the building of urban pipeline networks is far from finished.

Capacity management becomes an increasing concern to the functioning of the network. The growth of the Rotterdam pipeline into a regional network (and early beginnings of a national system) starts to necessitate an operational center that deals with the balancing of the regional and urban pipelines. An obvious necessity is the regulation of hydrogen gas flows and pressures, disturbance response and automatic protection. For hydrogen, the monitoring of flow balances and pipeline pressures throughout the nodes and links of the pipeline network needs to be safeguarded despite regular enlargements. The daily functioning of the network is alleviated through hydrogen storage, however. In this sense it is similar to natural gas and unlike electricity where supply and demand need to be constantly managed. Storage creates opportunities for the balancing of supply and demand as it presents back-up capacity when production is low or demand is high. It may also relieve pressure by allowing excess hydrogen to leave the pipeline network in case of capacity overload or blockade and help deal with seasonal demand fluctuations. As such, it takes the 'pressure' off the network, alleviating network intensity. Nevertheless, gas flows still require continuous monitoring in order to make use of this possibility. Moreover, the regional scope of the pipeline implies that a failure remains somewhat limited; the Arnhem-Nijmegen network would be unaffected, for example. Important to remember is that truck delivery is functionally disconnected from the pipeline network by the liquefaction process that is required and that truck distribution as such does not require any real-time operational balancing. Concerning tactical management, it is likely that the facilitation of unit commitment will struggle to keep up with demands for pipeline access and a growing scope of service. New access points are likely to be created to accommodate central hydrogen production from natural gas and new coal and biomass facilities on the one hand and filling stations and liquefaction-depot transfer facilities for trucks on the other. Meanwhile, older long-term contracts might hinder newer contracts, i.e. delivery via new hydrogen pipelines might find it difficult to get access to fuel stations that still have obligations to remaining onsite production facilities and truck distribution companies. The same goes for established vs. newer large-scale producers. In other words, while network boundaries are changing, the technical operation is likely to be based on an older version of the network. Unit commitment for truck companies remains essentially the same as in the previous phase, with the pipeline operator replacing onsite facilities. Maintenance scheduling is still a negligible activity considering the young age and developmental nature of the pipeline system at this point. However, some 'childhood diseases' may be expected. In this sense, trucks play an important role as back-up capacity should parts of the pipeline malfunction. Regarding strategic management, two developments require planning. First, to supply the increasing hydrogen demand, large-scale central natural gas production plants are replacing onsite production. Questions arise as to where to locate these central production facilities so that they can be cost-effective and near a pipeline entry point and whether or not to decommission certain onsite facilities. Second, coal and biomass start to become competitive sources. The integration of these sources, i.e. their accompanying production facilities, into the pipeline and truck distribution networks also needs to be planned and developed.

System management proves very challenging amidst the major changes in which the transition is situated by 2035. How to prevent major mismatches in a time of rapid growth of the network, production capacity, and fuel stations (and fuel cell vehicles)? Hydrogen production levels and network capacity need to match consumption patterns. Some supply and demand side management (production quota, subsidies, taxes, fuel cell vehicle stimulation, etc.) is required. Moreover, the maintenance of strategic reserves and excess production capacity is crucial: without sources, no hydrogen; without back-up capacity, no possibility to balance supply and demand. Hydrogen storage possibilities and trucks play a key role in this respect as they allow hydrogen to be shifted between generation plants, storage-liquefaction sites, the emerging pipeline network, and local fuel stations when needed. Regarding the quality of service, the replacement of various local hydrogen networks by the expanding pipelines starts to allow for competition among various hydrogen sources, most notably between natural gas, coal, and biomass. Renewables (mostly wind) are developing, but are still unlikely to compete with fossil sources without support, even when CCS costs are included in their prices, due to the economies of scale of the latter (Mueller-Langer et al. 2007). This warrants further government support for their development. A good balance needs to be found between ensuring coverage, i.e. availability, and the stimulation of renewables.

7.1.2.2 Allocating Technical Functions

According to the roadmap, the western region's hydrogen infrastructure is likely to be based on a few hydrogen sources and several central large-scale production sites, while traders are likely to be still absent in this formative hydrogen stage. In addition, we have chosen to ignore the remaining onsite facilities until step four, when we bring the onsite-truck centers back into the picture. Regarding the network, there is a single pipeline operator, a few truck distributors, and a few storage-liquefaction sites. Metering is not an entity for hydrogen as it is done by retail fuel stations in first instance with truck companies and liquefaction sites passing it on to the pipeline operator and producers. By now, finally, there should be around half a million fuel cell vehicles on the road, serviced by a hundreds, if not a thousand, fuel stations. The list is concluded by a single regulator. Let us now allocate the operational responsibilities of the technical functions to these entities.

Interoperability involves many entities. The establishment of norms and standards is mostly a regulatory issue, although it involves coordination among producers, network companies, storage-liquefaction facilities, and retailers. Compliance is mainly the task of the pipeline operator, central production facilities, and storage-liquefaction sites, because they form the entities where neglect is most damaging. Of course, truck companies and retailers also need to comply with standards, but the impact of their failures to do so tend to remain limited in effect. The planning and facilitation of interconnection of the pipeline network, the truck networks, and between both is mainly the responsibility of the pipeline operator and truck companies. It is likely that the pipeline operator takes the leading role in between both because of the direction of hydrogen gas flows from the pipeline to the trucks. Considering that storage-liquefaction facilities act as the transfer stations between both, they also play a role in smoothening interconnection. Primary responsibility for operational balancing and tactical management rests with the pipeline operator for the pipeline network and the overall infrastructure. Truck distribution companies that operate as an extension of the pipeline network are involved to a lesser extent. The former has actual balancing tasks, while the latter has not. Both deal with unit commitment though. There, producers are involved as hydrogen suppliers (weak direct involvement) and fuel stations as meterers and shippers hiring network capacity (weak direct involvement). Storage-liquefaction sites play an important supportive role, as does the regulator as a setter of access conditions. They do not actively manage capacity issues, however. The generation and fuel planning of strategic management in contrast mostly involves the central producers, pipeline operator, and truck companies. Finally, system management depends first and foremost on central producers (quality and quantity of hydrogen gas generated), the pipeline operator, and truck distributors, while fuel stations (for metering the quantity demanded) and storage-liquefaction facilities also play a big role in matching demand and supply. A regulator might additionally make the connection to any fuel station that is willing to sell hydrogen compulsory in order to promote availability. Lastly, the networks of sources and consumer behaviour may influence supply and demand. An overview is presented in Table 7.3 below.

Table 7.3 Contribution of entities per technical function in 2035

Entities	Amount	Inter-operability	Inter-connection	Capacity Management	System Management
Sources	Few	--	--	--	-
Central production	Few	+	--	+/-	+
Onsite production and liquefaction	Ignored	--	--	--	--
Trade	None	--	--	--	--
Pipeline transmission	One	+	++	++	+
Storage and liquefaction	Few	+	+/-	-/+	+/-
Truck distribution	Few	+/-	+	+	+
Metering	None	--	--	--	--
Retail / fuel stations	Hundreds to thousands	+/-	--	+/-	+/-
Consumption	Thousands to millions	--	--	--	-
Regulation	One	-/+	--	-/+	-/+

Legend: 6 degrees of involvement are distinguished from least to most:

--	No involvement.
-	Indirect involvement (entity affects operation or planning).
-/+	Supportive involvement (set ramifications, data providers, oversight).
+/-	Weak direct involvement in daily operations (entities involved in operations).
+	Strong direct involvement (key operational responsibilities).
++	Leading involvement (central coordinating entity, system operator).

7.1.2.3 Assessing Coordination Requirements

Considering interoperability, with the existence of hydrogen standards on various production means (for various sources), pipeline and truck distribution, and its use in fuel cell vehicles, the required control mechanisms seem in place. In addition, these standards are starting to present a dominant design around pipelines. This makes compliance with them more self-organizing, as deviation from them increasingly damages entities themselves economically. Moreover, access conditions to the pipeline network further disciplines entities to comply to standards if they wish to reach markets. In turn, regulatory monitoring becomes less a necessity and voluntary adjustment by entities more and more the norm. At the same time, the dominant role of pipelines in transportation of hydrogen increases the consequences of interoperability failures; if gas contents are not properly checked at the feed-in point, contamination spreads quickly and has a much larger impact area than that of onsite production or truck delivery. The scope of control and speed of adjustment for compliance now mostly involve the component level in the immediate- and short-term for pipelines and trucks respectively. As for the regulatory dimension, although it involves a system scope and short-term action, its criticality now has the equivalent of a subsystem considering that oversight is now basically entrusted to the pipeline operator who checks at feed-in points. For the planning of future developments, we see a similar movement due to the dominant design: from system to subsystem level, but still in the long term. While the national hydrogen infrastructure is still far from finished, future developments are better conceived as additions rather than alterations to the dominant design. The accompanying modes of organization are adherence to 'general framework conditions' for pipelines, 'self-monitoring and voluntary adjustment' for trucks, 'mutual monitoring and stimulated adjustment' for the regulator, and for future developments 'indicative planning'. The overall criticality is hence lower than in 2020: medium at its highest. While voluntary adjustment by autonomous entities would be sufficient in most cases to ensure that standards are upheld, the dynamic nature of this snapshot still calls for common operation based on agreement between autonomous entities for the time being in order to adapt to systemic changes if they would occur.

Interconnection moves to the center of attention as this phase marks the switch from onsite production and truck distribution to a central pipeline network supported by truck distribution. The scope of control of this 'two networks infrastructure' is caught somewhere between the system and subsystem. On the one hand, the regional size of the pipeline network and the still local nature of the remaining truck networks seem to point to a subsystem scope. On the other hand, these networks are increasingly connected shaping the typical transmission-distribution divide, the more so because local urban pipelines are also being developed. Of course, this holds for those areas in which the pipeline is connected to local distribution networks (Randstad area, but not the Arnhem-Nijmegen area). The speed of adjustment involves the short term for both pipelines and trucks (because despite instantaneous transport, storage possibilities and liquefaction create a buffer at the linkages or transfer stations). An important feature to note is the dynamic setting in which interconnection facilitation is to take place; how to keep up with connecting new entry and exit points and quickly developing network connections now that the planning issues of the previous snapshot change into daily network facilitation tasks in 2035? Considering that the pipeline network is redefining the overall infrastructure, we are inclined to argue that interconnectivity has become a systemic concern for the pipeline system and the adjacent truck delivery networks. The accompanying mode of organization is 'compulsory monitoring and stimulated adjustment'. Besides facilitation, new planning issues exist regarding the development of the national pipeline network and the further role of the local truck networks. Both are long-term systemic issues, leading to a mode of organization of 'directive planning'. Focusing on the very high criticality for facilitation, a central coordinating center that monitors and responds seems required. This is best done by the pipeline operator.

The growth of the regional pipeline system makes capacity management a critical issue in 2035. Its exact nature is difficult to assess, however. Regarding operational balancing, the pipeline network requires a central operator[170] along the lines of present-day natural gas in order to deal with hydrogen quality, flows and pressures, disturbance response and automatic protection. Truck delivery related to pipeline activities retains the lack of need for operational balancing. However, there is more to it than that if we wish to assess the scope and speed of the pipeline system. On the one hand, the pipeline directs national hydrogen flows despite its regional size, with the catch area being enhanced by truck delivery. Moreover, the pipeline network functions as a stand-alone system, not as a subsystem of another, more national system. On the other hand, the size of the pipeline system is still regional. Although it connects the west of the Netherlands (mainly the area between Rotterdam, Amsterdam, Utrecht, and Breda) and obtains the characteristic backbone feature of transmission grids, it at the same time is still of little consequence to the Arnhem-Nijmegen network or other more remote networks as such. Moreover, the smaller scope is accompanied by a relatively low network complexity in comparison with the current natural gas network.[171] Finally, as with natural gas, the speed of adjustment is alleviated through storage possibilities and the buffer possibility of storage-liquefaction between pipes and trucks. The question remains, however, in how far storage is sufficient to necessitate a short-term, but not immediate, response? Hydrogen flows still need to be monitored continuously despite storage possibilities. It seems that in the end we have a regional pipeline network that requires the mode of organization befitting a system scope of control and an immediate speed of adjustment, but one whose criticality should be accepted as being lower than one would usually associate with 'authorative supervision'. The main reason is that while pipeline operations may be highly critical, the consequences of failures are relatively manageable compared to the natural gas network, for example, especially because trucks are flexible enough to deliver hydrogen from storage sites to fuel stations on short notice. Tactical management becomes a highly critical function in 2035. The main challenge is to combine the need for tight coordination of unit commitment and scheduling of a pipeline network with the rapidly changing nature of hydrogen demand, supply, and transport capacity. On the one hand, capacity needs to be booked and executed in the short term (although facilitating long-term contracts may also be involved). Of course, the systemic role of the pipeline is also here contrasted by its still regional scope, while criticality is lessened by the possibilities for storage that may alleviate operations and the flexibility that trucks may offer in dealing with failures. Hence the scope is again stuck between the system and subsystem level. Truck delivery for its part retains its characteristics regarding unit commitment, though it now coordinates its actions with that of the pipeline: subsystem and short

[170] One single operator for both the regional pipeline and its local urban offshoots seems sufficient considering the relative simplicity of the network in terms of entry and especially exit points (retailers).

[171] Dynamics have no grip on operational balancing; it takes place in too short a time for the network to change in the meantime; hence the definition of T0 as a time in which all technical ramifications can be taken as a given.

term. On the other hand, the dynamic nature of the snapshot puts pressure on the drafting and execution of contracts (unit commitment and scheduling) in a setting where entry points (production sites), exit points (retail stations), and pipeline scope and capacity continuously and rapidly change. This requires a great degree of flexibility from an operator. If not met, demand and supply will fail to meet. Thus, whereas producers, the pipeline operator, truck companies, and retailers need to cooperate closely to coordinate hydrogen supply, transport capacity, and demand, these entities also need to remain flexible enough to be able to rapidly adjust to new circumstances.[172] As so often, a mix of both seems preferable. However, in the case of hydrogen, there might be a third option: strong central operation of the pipeline system, while utilizing trucks and storage possibilities as the flexible entities. This way, one may aim to have the pipeline operator coordinate network capacity, hydrogen producers, and fuel stations and allow truck distributors to fill in those gaps where the pipeline operator cannot deliver or lacks hydrogen input or transport capacity. As such, 'compulsory monitoring and enforced adjustment' are required for the pipeline system while truck delivery 'only' requires 'mutual monitoring and stimulated adjustment'. Strategic management also increases in criticality as generation and fuel planning issues move from the subsystem to the system scope considering that despite the regional scope of the pipeline network, new production facilities are meant to serve the national pipeline network as outlined by the roadmap. The speed of adjustment may also move from long-term planning to medium-term development now that the plans of the previous snapshot become matters of execution. Hence a 'controlled allocation mechanism' and 'directive planning' are necessary. The planning for truck networks stays at the subsystem scope, but now needs to specifically align to pipeline developments, requiring a 'guided allocation mechanism' and 'indicative planning'. To sum up, capacity management increases in criticality but remains largely limited to the western pipeline-truck system. The Arnhem-Nijmegen center and other remote areas are the same as in 2020. The flexibility of trucks goes a long way in dealing with the dynamic nature of this snapshot, but cannot change the fact that central operation and tight coordination of the pipeline network are required. Criticality is hence very high, requiring more than just the continuous coordination between key entities: a central coordinating center that monitors and responds but that realizes the usefulness of the flexibility of trucks.

Concerning system management, the balancing of supply and demand will prove very challenging in this phase. The main reason is that the management of a pipeline system in a rapidly changing environment requires both tight coordination and great flexibility, as was noted above. On the one hand retailers, producers, and the pipeline operator need to tightly coordinate hydrogen demand, supply, and transport capacity. On the other hand, these entities should remain flexible so as to be able to

[172] This is similar to the discussion of complexity in chapter 5. While both NAT and Künneke et al. would agree on the fact that increasing complexity implies a higher criticality, they differed on how to best facilitate it. Whereas the former believed that decentralized operation would be best suited to deal with problems quickly and locally before they can cascade, the latter stated that centralized coordination would be better suited to deal with complex failures as central operators have the overview.

quickly adjust to new circumstances. The solution for tactical capacity management also holds true for system management: a key role lies in the use of trucks and storage depots to manage any demand-supply mismatches, although some supply- and demand-side management by regulators may also aid system management. A key role also lies with producers; they should ensure strategic reserves of hydrogen sources and sufficient productive capacity. This involves for the pipeline the system level in the short and medium term for facilitation and preparation respectively, requiring 'compulsory monitoring and enforced adjustment' and a 'controlled allocation mechanism'. The truck delivery operates adjusted to the pipelines on the subsystem level in the short and medium terms: 'mutual monitoring and stimulated adjustment' and a 'guided allocation mechanism'. Regarding quality of service, to stimulate competition among hydrogen sources and the greening of hydrogen production, some sector specific regulation seems required to support the use of both CCS and hydrogen from biomass. Some stimulation of fuel stations in rural areas might furthermore be required to increase availability and area coverage. In the end, the criticality of system management is very high due to the rapid growth of production and demand volumes and the incomplete nature of the networks. A central coordinating center that monitors and responds seems required.

Summing up, overall criticality in 2035 is high. Interconnection and system management have become important matters that require immediate and constant attention and systemic coordination, while capacity management has started to play a role in the pipeline network. Only interoperability seems to be less in terms of criticality as the basic codes and standards have been developed. The particular challenge of this phase in terms of organization was how to combine the need for coordination and central guidance of the operation of the pipeline system and its interconnections with the flexibility required to adjust quickly to new infrastructure development (new fuel stations, new production sites etc.). The coordination requirements are summarized in Table 7.4 below.

Table 7.4 Coordination requirements of technical functions for hydrogen in 2035

	Interoperability	Interconnection	Capacity management	System management
Coordination requirements	-/+	+	+	+

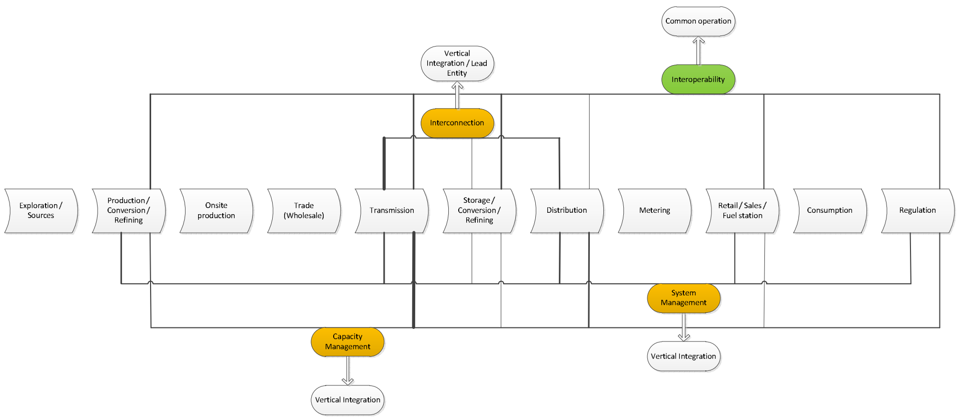
Legend: 6 degrees of criticality / central coordination requirements can be distinguished:

- - - Not critical; autonomous entities act without need for coordination.
- - Low criticality; autonomous entities that voluntarily adjust operation to a common rule/goal.
- -/+ Medium criticality; common operation based on agreement between autonomous entities.
- +/- High criticality; continuous coordination between key entities.
- + Very high criticality; central coordinating center that monitors and responds.
- ++ Most critical; central coordinating center that dictates and supervises.

7.1.2.4 Towards an Organizational Structure for 2035

Combining steps two and three per technical function, we find that interoperability has become less critical due to the framework offered by existing standards and the incremental nature of new standards, but involves more entities than in 2020. This shifts the organizational structure towards that of common operation. Interconnectivity becomes a very important issue to deal with in the rapidly changing environment and mostly involves the pipeline operator and truck distributors. High criticality implies tight coordination between the two whereby the pipeline operator is the leading entity while truck companies fill in those niches pipelines cannot. Capacity management involves many entities and is very highly critical. To manage the energy flows within the pipeline system and between pipelines and trucks while ensuring sufficient production to meet retail demand seems to require central operation and continuous, immediate, and broad coordination. Vertical integration is hence advised. System management similarly involves many entities that are roughly equally involved, although producers and retailers play a more prominent role (this in contrast to capacity management where network and truck operators play a more prominent role). The stringent coordination required to ensure that demand and supply match seems to be best guaranteed by a vertically integrated structure. The result can be seen in Figure 7.2 below.

Figure 7.2 Towards an organizational structure for 2035



Legend: No and indirect involvement = no line
Supportive and weak direct involvement = normal line
Strong direct involvement = bold line
Leading involvement = fat line

Not critical = white
Low criticality = blue
Medium criticality = green
High criticality = yellow
Very high criticality = orange
Most critical = red

The biggest challenge in this snapshot is finding a way to combine the need for flexibility necessary to introduce and develop hydrogen as a motor fuel with the central technical coordination required for operating the pipeline network and the interconnected local truck networks. Another challenge is to integrate the necessary organizational structure of the western pipeline-truck network with that of the onsite-truck networks existing in other parts of the country. Regarding the former, in 2035 the key entities are the pipeline operator, truck distribution companies, and central producers, while fuel stations, storage-liquefaction sites, and the regulator play a secondary role in maintaining reliability. Criticality is high for interconnection, system management, and capacity management, and medium for interoperability. Putting the picture together we see that while the pipeline operator functions as the central organization, it needs to coordinate its actions very closely with the other entities (mostly with truck distributors) in order to ensure system functioning in a rapidly changing environment. According to the reasoning of the framework, the most appropriate organizational structure seems to be the vertically integrated firm. Such a strong statement, however, seems to run counter to the flexibility demanded by the dynamism of the broader setting. In other words, it seems that the result is strongly biased towards dealing with daily operation at a specific moment in time to the neglect of the rapid changes that the infrastructure undergoes. Considering the objective of the framework and its comparative static nature, this was perhaps to be expected. The lesson we can learn from this is that while the framework seems well-equipped to estimate organizational requirements in relatively stable conditions, it might do less well in rapidly changing environments.

Concerning the overall Dutch hydrogen infrastructure organizational structure, how to proceed, considering the pipeline-truck and onsite-truck networks are so different? It is rather questionable as to whether taking the average of the organizational requirements would do any good: it is either too centralized for one or lacks sufficient coordination for the other. It seems better to treat them as separately organized networks that, when combined, operate the overall infrastructure. Hence, we need to realize that a single infrastructure might require multiple organizational structures. In other words, it seems that the framework should be applied to one network at a time. While we managed to treat the pipeline and truck networks together in this case, we have basically done so by discussing them separately for interconnection and capacity management throughout. This was considered desirable because they together transport hydrogen from producers to retailers (and as such form one infrastructure) and in order to illustrate this very point. Yet because trucks operated in accordance with pipelines, framework application remained feasible since it allowed for a focus on pipelines as a sort of transmission network to which the trucks acted as local distribution networks. Through this order of importance in operational responsibilities, the organizational structure befitting the pipeline network could be justified, while the deliberate flexible nature of the use of trucks could be fitted within this larger structure. It will be more difficult to combine two different transmission networks, for example when pipelines in the west and trucks in the east of the country play the same role. In that case, we simply face two different hydrogen networks that together ensure nationwide service.

7.1.3 2050; A National Hydrogen Pipeline Network

This phase characterizes itself through the existence of a national pipeline network that is extended by truck distribution in remote rural areas, mostly in the north of the Netherlands. These extensions are technically linked (in that they continue the supply chain) but operationally separated through buffers such as storage depots and/or liquefaction sites. Trucks may also play a supporting role to pipelines in case of emergencies. In addition, some onsite facilities supported by truck distribution remain in the north of the country. Large-scale production from coal with carbon capture and storage has replaced natural gas as the main source, followed by biomass and wind. Other renewables also finally become competitive options. Fuel stations cover the western, southern, and eastern urban areas densely. In general, around 2050 the situation is stable yet complex. To study this snapshot, let us focus on the national pipeline system and truck distribution extensions, ignoring the few remaining user centers based on onsite facilities and truck support since they now cover only a marginal part of the country.

7.1.3.1 Critical Technical Functions and Control Mechanisms

By 2050 it is likely that most interoperability issues have already been taken care of during the decades leading up to it. Without harmonizing the quality of hydrogen with its production and storage methods, its distribution means, and fuel cell vehicles, the growth to get to this phase would simply not have been able to occur. Moreover, by now a dominant design around the pipeline system has emerged for which the standards have been drafted and to which compliance is a practical necessity for individual entities wishing to utilize the infrastructure (for producers to reach markets or retailers to acquire hydrogen), for the efficiency of the overall infrastructure (for the nodes and links to be well-attuned), and for connection to international networks. Access conditions for the national pipeline network further represent an additional control mechanism. In turn, regulatory oversight need not encompass the entire infrastructure, but may focus on occasionally checking the operator's adherence to standards and procedures. Only the newly created standards for new renewable sources and new fuel cell technologies may still require some regulatory oversight. However, as long as electrolysis is used, hydrogen purity should not be much of a problem since it generates the purest form (in contrast to hydrogen from local biomass for example). Please be reminded that the distributed production of hydrogen via electrolysis is absent in the roadmap; this is likely because it would be much more efficient to use the electricity generated by renewables rather than turning it into hydrogen. Even if hydrogen were to be produced for personal use, it would not affect the pipeline infrastructure as such, thus causing no interoperability problems beyond the personal scope. It hence seems that in 2050 the tracking of market developments, new services and applications, new sources and production methods, and new distribution and storage means remain the main issues to address to ensure complementarity. This mostly concerns the development of more futuristic renewable hydrogen sources and storage methods like the use of carbon hydrides or nanotubes.

Regarding interconnection, by 2050 the big shift to a national pipeline network should have by and large been achieved for delivery to the main Dutch urban areas and the highways in between. This means that the four major issues of the previous phase[173] no longer require development but only further facilitation. Facilitation is likely done by a single operator, despite the national and local urban network divide, considering the limited amount of entry (central facilities) and exit points (fuel stations) if compared to the current natural gas system.[174] Trucks only play a role as back-ups in urban areas, i.e. those areas where the pipeline covers transport, as the pipelines now are able to cover the whole west, south and east of the Netherlands. Nevertheless, new issues emerge that require planning and development. First, despite the expansion of the pipeline infrastructure from Rotterdam into the Netherlands, some more remote local networks relying on onsite production and liquid hydrogen trucks continue to exist. In the end, it will be a cost issue whether or not to incorporate these remote regions into the pipeline network. Otherwise, trucks could be used as rural extensions of the pipeline network. Such extensions require liquefaction and constitute essentially the same linkages to the hydrogen pipelines as in 2035. Of course, the use of trucks in this fashion also creates interconnection facilitation issues for truck companies. As these are basically the same as in 2020 and 2035 in nature, they require no further discussion here. Second, centrally produced biomass and wind are expected to slowly replace natural gas and coal over time as the dominant hydrogen source in rural areas where they can compete; so some attention is still required when it comes to the construction and connection of future hydrogen production facilities. Moreover, centrally produced hydrogen from other renewables may start to develop in urban areas. Another new development in this phase is the possibility of connecting the national network to foreign networks in Belgium and Germany (Antwerp region and Ruhr area; see the roadmap) or even further into the EU. A lot will depend on Germany and Belgium developing their networks. In contrast to the previous phase, however, most interconnection issues represent additions or incremental adjustments to the existing national pipeline network rather than the building of a whole new infrastructure. The notable exception, of course, is the possible international connection, which may open up new hydrogen flows altogether.

The nature of capacity management has not changed much since 2035. Nevertheless, there are some new considerations. First, the national network by 2050 is much larger in scope than the regional one of 2035. Second, network complexity is much higher because the amount of access points, the variety of sources (inputs), and number of filling stations (output) has increased. Third, the intensity of network use, i.e. the volume of hydrogen transported, has risen. The pipeline network now is expected to deal with all domestic and foreign sources of hydrogen. Especially the fact

[173] These were: 1) the integration of regional and local onsite networks into the expanding national infrastructure; 2) the building of urban networks; 3) the connection to near vicinity areas; and 4) the linking of hydrogen networks to those of gas, coal and biomass.

[174] Although there may be more entry points for hydrogen than for gas considering its diverse sources and means of production, the few thousand fuel stations pale in comparison to the 6.7 million households that use gas.

that hydrogen knows many sources creates a heightened need for the facilitation of multiple inputs into the pipeline. For example, how to manage hydrogen produced from wind power on the North Sea, from coal in Limburg, from natural gas in Groningen or Rotterdam or from rural biomass? Moreover, a hydrogen network will involve a mixture of flows: from NL to EU, from EU to NL, from NL to NL and from EU to EU. In terms of operational balancing, while the core functions of regulation and control, automatic protection, and disturbance response (and the role of hydrogen storage possibilities therein) basically remain the same as in 2035, they need to be performed under more stringent conditions, i.e. under stricter time constraints due to the intensity and for a larger and more complex network. The truck distribution that extends hydrogen pipelines in the north does not require operational balancing (see 2020 and 2035). Tactical management has become both more and less critical in 2050. On the one hand, unit commitment and maintenance may be more challenging because the pipeline network has increased in scope, intensity, and complexity. In addition, competition for pipeline access between producers using renewable or fossil hydrogen sources is now possible, due to the increasing use and lowering price of renewable hydrogen sources. This gives rise to complex user rights issues regarding pipeline capacity.[175] Principles of undiscriminating third party access will need to be upheld (or ignored if renewables are to be stimulated, for example). This also opens up a possibility for hydrogen trade and spot markets. Finally, in 2050 issues concerning network maintenance also start to interfere with network management. On the other hand, contrary to this picture of increasing intensity and complexity of hydrogen gas flows stands the fact that the situation in 2050 is more stable than in 2035 because a core network already has been developed. This alleviates tactical management because it reduces uncertainty. Interruptions due to generation and network capacity development or opening interconnections to fuel stations in new user centers now give way for decisions about starting up and shutting down generation and which pipelines to use. Moreover, a certain operational routine will have developed; over time hydrogen producers, retailers, and the network operator will have established certain norms and procedures to deal with each other. The effect of this is hard to estimate, but it seems safe to state that it helps in dealing with complexity. Truck distribution in contrast has become simpler. No longer need urban retail stations be supplied, but just a few rural ones. Complexity has lowered for them, as has intensity. Their operational relation to the hydrogen pipelines remains essentially the same as in 2035, with liquefaction acting as a buffer. Yet instead of acting as a distribution operator of sorts, trucks are now better seen as just another exit point, like any retailer. Despite this smaller role in the overall infrastructure, unit commitment does continue to play an important part in truck distributors operations.

[175] The organization is shaped by the existing contracts and user rights that already account for much of the available network capacity. The amount of free network capacity is likely to be determined by the space that long-term contracts on primary markets leave for secondary, short-term markets. In this light storage facilities create back-up capacity that is economically interesting for spot markets. Thus tactical management is both more stable because of existing structures and long-term contract obligations and more flexible due to short-term market opportunities.

Concerning strategic management, new issues of fuel, generation, and network planning have replaced the old. While the national pipeline network is finally up and running, new possibilities for renewable hydrogen production have become competitive. Due to the potential for their local generation, preparations need to be made if, how, and where to connect them to the pipeline. In the meantime, fossil fuel based hydrogen generation facilities are being phased out, making the matter more complex. In addition, local networks keep growing incrementally and other uses than motor fuel might be found for hydrogen. Sufficient reason for planning thus remains.

Regarding system management, the situation is less dynamic and uncertain, yet more intense and complex if compared to 2035. On the one hand, while production and consumption continue to grow, they do so incrementally. In addition, a core pipeline exists that will remain largely the same for the long term. In general, as hydrogen becomes an increasingly mature market, production, distribution, and demand patterns are established making aligning supply and demand easier. On the other hand, the fact that natural gas is increasingly being replaced by coal, biomass, and wind (increasing the amount of entry points), that the pipeline network now encompasses a fully developed national backbone with several urban segments, that there are increasing numbers of fuel stations to be served (exit points), and that the volume of flows through the network has risen, increases the importance of pipeline operations for overall reliability. Thus criticality shifts from dealing with change and fluctuations to dealing with complexity and intensity in the pipeline network. This however also shifts criticality from system management to capacity management. In this light, the role of trucks changes from managing demand and supply fluctuations to assisting the pipeline network in case of emergencies. Trucks remain more important, however, in more rural areas for ensuring true national coverage. Concerning the preferences, availability and affordability should no longer be much of an issue. However, the time is ripe to address sustainability now that hydrogen production from renewables can be expected to be cost-competitive with production from fossil sources with CCS. Nevertheless, the share of renewable hydrogen in total hydrogen production is still rather low in 2050. As a transition to hydrogen was initially undertaken to make mobility 'green', some government stimulation to ensure that hydrogen from renewable sources continues to develop might be desirable. Moreover, while CCS helps make natural gas and coal environmentally friendly, energy supply security concerns would still make domestically produced renewables preferable.

7.1.3.2 Allocating Technical Functions

In essence, the national hydrogen pipeline network is very similar to natural gas transmission today. Nevertheless, there are two major differences. First, hydrogen is an energy carrier that knows many possible sources, allowing for both centralized and decentralized production, and that has fuel stations as customers, a far smaller amount than the number of industries and households utilizing natural gas today. This results in a network that is more complex in terms of entry points and less complex in terms of exit points. Second, and consequently, the hydrogen network essentially lacks the typical transmission-distribution divide. There is no need for a dense distribution network with separate operation. The pipes running from the main high-pressure hydrogen pipes to the local urban fuel stations and those along highways are far less in terms of number and scope. Hence it is likely that a national operator does not need local pipeline operators to manage hydrogen flows. Of course, hydrogen does have the additional factor of being linked to truck delivery networks, although they are operationally separated by the liquefaction process. In terms of infrastructure entities, there are now a few sources dominant in hydrogen production (with many looming in the next decades), a few central production sites (mostly in the Rotterdam area, but increasingly throughout the Netherlands), and a few traders that are likely to have started to do business (especially now that the pipeline also has international connections). Regarding the network, there is one pipeline transmission operator, a few storage and liquefaction sites that are situated between the pipeline exit points and a few truck distribution companies. There is no entity metering because that function is part of the fuel stations (retail). Next, there should be by now a few million fuel cell vehicles driving around the country fuelled by a few thousand hydrogen stations. Finally, a single regulator that monitors competition and social obligations in the hydrogen sector is also likely to be present.

Interoperability facilitation is the combined task of the transmission pipeline operator (involvement as controller of hydrogen compounds at feed-in points), central producers (strong direct involvement in production, especially because of the various different hydrogen sources), and storage and liquefaction sites (strong direct involvement in conversion without which there is no connection). Next to that, truck distribution companies and retail also need to comply to standards. The regulator plays a decreasing role in enforcing standards (now taken over by the pipeline operator) but the planning and establishment of new standards is still mostly a regulatory issue, with the other entities involved in negotiations. The planning and facilitation of interconnection of the pipeline network, truck networks, and between the pipeline and truck networks are the responsibility of the pipeline operator and truck companies (leading and strong direct involvement respectively). Storage-liquefaction sites play an important role in the latter. As with natural gas, the operational, tactical, and strategic capacity management form the most critical of activities and involves coordination among many entities. Operational balancing responsibilities, e.g. hydrogen transport and quality, disturbance response, and automatic protection, rest solely with the pipeline operator (leading involvement). Tactical balancing, e.g. maintenance scheduling and unit commitment, in contrast involves many entities, next to the pipeline operator, which has the leading involvement. Storage-liquefaction sites are involved as the entities metering the volume of hydrogen exiting the pipeline (weak direct involvement). They are in this sense similar to the retail outlets that act as shippers hiring network capacity to deliver gas to them via the pipeline network (weak direct involvement). Though operational balancing is not an issue for trucks, truck distribution companies act as an intermediary between rural retail outlets and liquefaction sites. The latter in turn are relevant for balancing. Producers, traders, and the regulator are involved as hydrogen suppliers (weak direct involvement), as intermediaries between producers and network companies that enhance overall efficiency if international network connections allow for it (indirect involvement), and as those that define the conditions for access respectively (supportive involvement). They matter, but do not actively manage capacity issues. The generation and fuel planning of strategic management primarily involves the central producers and pipeline operator and secondarily onsite producers and truck companies. Finally, while system management still depends on central producers (quality and quantity of hydrogen gas generated) and fuel stations for metering (quantity demanded), the role of the pipeline operator becomes increasingly crucial. Storage and liquefaction sites help in bringing the hydrogen from the pipeline to rural areas. Truck delivery companies still play a role in matching demand and supply in rural areas and may assist the pipeline network in urban areas in case of emergencies. Traders also may help the operator by managing supply liquidity. Next, the regulator has no real technical role to play, but it may set targets for renewable hydrogen shares to stimulate certain sources over others. It might also still make the connection of uncompetitive fuel stations compulsory to ensure national coverage. Lastly, consumers and sources affect demand and supply. The result is summarized in Table 7.5 below.

Table 7.5 Contribution of entities per technical function in 2050

Entities	Amount	Inter-operability	Inter-connection	Capacity Management	System Management
Sources	Few	--	--	--	-
Central production	Few	+	--	+/-	+
Onsite production and liquefaction	Ignored	--	--	--	--
Trade	Few	--	--	-	-/+
Pipeline transmission	One	+	++	++	+
Storage and liquefaction	Few	+	+/-	+/-	+/-
Truck distribution	Few	+/-	+	-/+	+
Metering	None	--	--	--	--
Retail / fuel stations	Hundreds to thousands	+/-	--	+/-	+/-
Consumption	Millions	--	--	--	-
Regulation	One	-/+	--	-/+	-/+

Legend: 6 degrees of involvement are distinguished from least to most:

--	No involvement.
-	Indirect involvement (entity affects operation or planning).
-/+	Supportive involvement (set ramifications, data providers, oversight).
+/-	Weak direct involvement in daily operations (entities involved in operations).
+	Strong direct involvement (key operational responsibilities).
++	Leading involvement (central coordinating entity, system operator).

7.1.3.3 Assessing Coordination Requirements

In 2050, the adherence to standards is considered to be self-organizing because compliance to the dominant design and pipeline access conditions has become an operational necessity for entities. In turn, regulatory enforcement is either no longer needed or focused on the pipeline operator, essentially making standard adherence a component level issue. The difference between pipelines and truck based networks remains, however (immediate and short term). The accompanying modes of organization become 'upholding general framework conditions' and 'self-monitoring and voluntary adjustment'. With the harmonization of supply chain specifics essentially achieved, interoperability becomes mostly a planning issue for the long term by 2050. New developments and technological opportunities still need to be kept an eye on. However, because these will add to rather than redefine the pipeline network, coordination is no longer required. For example, hydrogen production from renewables can be attached to the infrastructure at any time if they comply with existing standards. In turn, the planning for future developments becomes an issue for individual entities, i.e. takes place on the component level. Of course, planning still involves the long term. Hence 'decentral planning' is sufficient. This lowers criticality and the need for central coordination further as compared to 2035. In the end, criticality is somewhere between low and medium, requiring either autonomous entities that voluntarily adjust operation to a common rule/goal or, in case of the pipeline operator, a more controlling function to check whether operational agreements between producers and itself are being observed.

Interconnectivity largely requires the same coordination as in since 2035, but for different reasons. The main development issues of the previous phase have become a matter of continuous facilitation, while new issues have emerged that require further planning and development. For the Netherlands, however, these mainly entail incremental additions to an existing system, rather than developments that will radically alter the infrastructure itself. Yet connections to foreign hydrogen pipelines may have a significant impact. Regarding facilitation, the main issues revolve around the connection between pipes, between pipes and trucks, and linking new production facilities to the pipeline network. For pipelines, this involves the system level and the short term (again storage possibilities alleviate criticality by creating a buffer). For trucks it involves the subsystem and the short term. This leads to modes of organization of 'compulsory monitoring and enforced adjustment' and 'mutual monitoring and stimulated adjustment' respectively. Concerning development, additions to the national pipeline network involve the system level in the medium term, while for truck networks they involve the subsystem level on the medium term (the combination onsite and trucks and as extension for pipelines). Matching modes of organization are 'controlled allocation mechanism' and 'guided allocation mechanism' respectively. However, if we take the incremental, flexible, and non-integrated nature of local truck network connections into account, it seems appropriate to nuance them as if they concern the component level. This would then involve a 'competitive allocation mechanism'. The same cannot be said for the pipeline system, as international connections need to be coordinated at the national level. However, at the same time, a more European approach might help to facilitate the ability to manage new cross-border hydrogen flows. The planning of future connections is similarly divided. It involves both national and international connections for the pipeline system and component level issues for truck networks. Obviously, both planning issues still involve the long term. Hence complementary modes of organizations are 'directive planning' and 'decentral planning'. In all, interconnection has shifted from running a simple but unfinished set of networks to the facilitation of a complex but mature infrastructure, and from a pipeline and truck system to a pipeline-only system and a truck-only system with the buffer of liquefaction. In the end, interconnection is less critical due to the fact that domestic facilitation, planning, and development issues are more incremental in nature and because it involves less coordination among entities but seems to primarily be the responsibility of the pipeline operator. On the other hand, facilitating international connections alongside national and local ones may bring new challenges. The high criticality of facilitation is best ensured by continuous coordination between key entities while the operator may take a leadership role.

By 2050, the daily operational balancing of the national network emerges as the most critical technical function. Not only has the pipeline network grown from a regional to a tightly integrated national system, but also have possible gas flows become more complex and intense due to the increasing diversity of hydrogen sources, the increasing amount of production sites and filling stations, and the increasing volume of hydrogen gas transported. This puts pressure on network capacity, in turn increasing criticality levels. Obviously, the national pipeline network has a systemic scope. Hydrogen storage and liquefaction sites for truck distribution might be connected to pipelines in a supply chain sense, but the necessary liquefaction represents a buffer that separates the truck and pipeline network in terms of operation. Concerning the speed of adjustment, hydrogen gas flows and quality within the national pipeline network need to be managed and emergency procedures need to be in place in case of failures or unexpected events. This needs to be done on the spot, although storage possibilities again alleviate criticality. As in 2035, the immediate and short terms are involved. In all, operational balancing involves 'authorative supervision' and 'compulsory monitoring and enforced adjustment'. Truck delivery does not require operational balancing. Concerning the tactical operation, the main question pertains to whether and how much the increasing stability and presence of routines offsets the increase in network scope and flow complexity. In any case, strict time constraints remain, because most actions need to be executed in the short term (unit commitment, spot markets, maintenance scheduling). As in 2035, some system level 'compulsory monitoring and enforced adjustment' are required. Regarding strategic management of the pipeline network, new planning and development issues related to renewable sources merely replace those of coal and biomass, i.e. the planning for new decentral production facilities instead of central ones. As such, strategic management again is a systemic long- and medium-term issue for planning and development respectively. Hence, the modes of organization continue to be 'directive planning' and a 'controlled allocation mechanism'. The long-term planning of trucks does not affect the overall system. Their concerns are mainly related to filling those gaps in coverage left by pipelines (and occasionally supporting local onsite facilities). These are concerns of the long term and subsystem level because truck companies will need to keep the pipeline system in mind. Overall, criticality is very high for capacity management due to the central role of the pipeline network, which necessitates a control center to operate the infrastructure.

Concerning the alignment of supply and demand, this phase is relatively stable compared to the previous. With an existing central pipeline network, a maturing infrastructure, and established demand and supply patterns, no major changes regarding supply and demand in terms of quantity are expected in the short run. Only an incremental but steady increase in both demand and supply over the long run is expected. Moreover, hydrogen's possibilities for storage, its various sources and related production facilities that are located throughout the country (albeit mostly in the west of the Netherlands), and the supporting role of trucks (as back-ups in case of emergencies and as a distribution means to remote regions) ensure that hydrogen reaches filling stations comparatively easily as compared to 2035. On the other hand, there is increased dependence on the pipeline network, while at the same time the pipeline operator needs to coordinate with many other entities. Moreover, system management still involves a systemic scope and the short and medium terms for facilitation and preparations. In other words, 'compulsory monitoring and enforced adjustment' and a 'controlled allocation' are the accompanying modes of organization. However, criticality is likely to be lower due to the many favourable infrastructure and situational features than the modes of organization indicate. Let us therefore conclude that the coordination requirements are best captured by the actions mentioned under the subsystem for the short and medium terms, or high criticality (and not the very high of 2035). Concerning the use of more renewable sources, the competition that now becomes possible between various sources opens up new possibilities for system management. If one source is not available, another might be. If renewables are the goal, however, and not just using hydrogen as a motor fuel, then regulation and subsidies might remain necessary to further increase the share of renewables in the overall mix of hydrogen sources. Availability and affordability should not be a problem.

Summing up, the overall level of criticality for a hydrogen network in 2050 is high, but for different reasons than in 2035. Whereas now the level of complexity and intensity has risen and a national pipeline network exists, creating challenges of capacity management, in 2035 it was the matching of supply and demand and ensuring connectivity in a very dynamic setting that posed challenges of interconnection and system management. Interoperability finally seems mostly solved as compliance to codes and standards has become of self-interest for the entities involved and inputs are checked by the pipeline operator. The coordination requirements are summarized in Table 7.6.

Table 7.6 Coordination requirements of technical functions for hydrogen in 2050

	Interoperability	Interconnection	Capacity management	System management
Coordination requirements	-	+	++	+/-

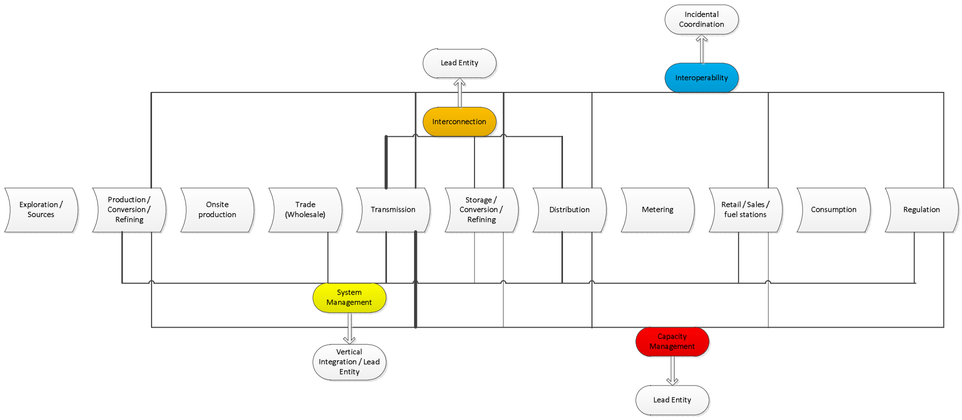
Legend: 6 degrees of criticality / central coordination requirements can be distinguished:

- -	Not critical; autonomous entities act without need for coordination.
-	Low criticality; autonomous entities that voluntarily adjust operation to a common rule/goal.
-/+	Medium criticality; common operation based on agreement between autonomous entities.
+/-	High criticality; continuous coordination between key entities.
+	Very high criticality; central coordinating center that monitors and responds.
++	Most critical; central coordinating center that dictates and supervises.

7.1.3.4 Towards an Organizational Structure for 2050

Looking at the hydrogen system in 2050, interoperability seems to have become a non-critical issue, although various entities may still develop new technologies in the long term. Yet developers of these technologies need to keep pipeline access conditions and fuel cell specifics in mind if they are to be used. As this is in the self-interest to all entities, incidental coordination among the sector's major players seems sufficient. Interconnection remains a critical issue, albeit for new reasons, and is the prime responsibility of the hydrogen pipeline operator while truck delivery operates in accordance with it. The structure of a lead organization fits here neatly. Capacity management becomes the center of operations due to its high criticality and many entities involved. Suitable organizational structures would be both vertical integration and lead entity depending on the weight one attaches to the role of producers, meterers, etc. in relation to the TSO. This study considers the deciding point to be that factual operations are done by the TSO while the other entities present the necessary information (demand) and hydrogen (supply). While their actions are important, the key role of the TSO in terms of operational balancing seems to suggest a lead entity structure. System management, finally, involves many entities and a high degree of criticality favouring central coordination through vertical integration. Nevertheless, the central role of the pipeline network in linking supply and demand and the increasing variety of hydrogen sources that can be utilized may allow for the TSO to act as the lead entity here as well.

Figure 7.3 Towards an organizational structure for 2050



Legend: No and indirect involvement = no line
Supportive and weak direct involvement = normal line
Strong direct involvement = bold line
Leading involvement = fat line

Not critical = white
Low criticality = blue
Medium criticality = green
High criticality = yellow
Very high criticality = orange
Most critical = red

The key player in the technical operation of the hydrogen infrastructure in 2050 appears to be the pipeline operator while truck distributors, central producers, retailers, storage and liquefaction sites, and the regulator have become of secondary importance. If we take the pipeline operator as the core entity for maintaining reliability and combine that with the knowledge that criticality is located in capacity management and interconnection, and that these require central coordination, we arrive at the same lead organizational structure that we found for our natural gas case in chapter 5. Vertical integration of production and distribution is not a technical necessity, due to hydrogen's storage possibilities and the possibility to generate hydrogen from a variety of sources at a various different facilities. Vertical integration with fuel stations might be lucrative business, but has no technical necessity. The current unbundled structure of natural gas with its public ownership and private operation of the network by a monopolist network company under sector specific regulation, combined with private production, trade, truck distribution, retail / fuel stations, all vertically separated from the pipeline network, comes to mind here as the best suited organizational structure for hydrogen.

7.2 Results and Reflections

With the organizational structures for the various stages of the hydrogen roadmap identified, it is time to sum up the changes in technological characteristics and organizational structures and discuss the experiences made in its application for further refinement of the framework.

7.2.1 An Organizational Roadmap

We have come a long way since the presentation of the hydrogen roadmap in the previous chapter. With the help of the framework, we are now able to present a complementary organizational roadmap. Let us quickly revisit the snapshots and sum up the findings.

For 2020, the roadmap envisioned three independent hydrogen user centers. Production was based on small-scale onsite SMR from natural gas, wherein the truck delivery of hydrogen from onsite faculties to other filling stations nearby serves as the true hydrogen network. In addition, some use of industrially produced hydrogen was also considered. The lack of an infrastructural connection between the user centers made for a simple (i.e. not complex) set-up wherein a few producers and retailers dominate the individual early user centers. In 2020 interoperability is the biggest concern if we follow the framework. Norms and values need to be set and adhered to by the entities involved and the proliferation of different standards managed / prevented. Interconnection and system management are marginal issues only; on the one hand the demand for hydrogen needs to be stimulated in areas further removed from onsite production facilities for the hydrogen uptake to proceed; on the other hand tanker truck companies should coordinate the operation of their networks with those of onsite producers who might themselves provide similar services. Capacity management can be neglected considering the focus on onsite production and the flexible capacity that truck distribution entails. Concerning responsibility allocation, we saw that onsite producers, truck delivery companies, retailers, and a regulator were roughly equally involved, albeit for different functions (planning or daily operations). Of course, onsite producers and retailers were often one and the same, while truck delivery might be integrated into producers (no technical necessity, but economic preference based). Hence operational responsibilities within the user centers might be centered in a core entity (onsite producer) or evenly distributed among the entities involved within each user center. In terms of criticality, in 2020 matters of interoperability, and to a lesser extent interconnectivity and system management, necessitated some coordination. This mainly took the form of the setting of standards through agreement with stakeholders in the long term and their facilitation by entities and regulatory oversight in the short term. In addition, there was the long-term planning of interconnectivity to facilitate network build-up. Some additional measures to ensure supply meets demand were also required. The combination of low criticality and fragmented operational responsibilities from a national perspective led to an organizational structure that resembled incidental coordination. However, it was also noted that it was likely to contain elements of common operation if the entities involved are determined to follow the roadmap and in that light need to make plans for future interconnection of the three centers, making adherence to the same standards of great importance.

In 2035 the roadmap presented an emerging national hydrogen pipeline network in the Randstad / west of the Netherlands, replacing local small-scale onsite production with large-scale central hydrogen facilities based on natural gas, coal and biomass with CCS. The role of truck distribution also changed from deliveries to urban to more suburban and rural fuel stations, playing the role of an extension of the pipeline network, and from a core transport means to the role of back-up capacity in case of emergencies in urban areas. The coming of the pipeline system also heralded a quasi transmission-distribution divide[176], connecting the early user centers on the one hand while forming urban pipeline networks on the other, and took place during a time of major growth in both hydrogen demand and supply. In 2035 interconnection and system management become the most important technical functions. This is mostly because the demand for and production of hydrogen increase rapidly in this dynamic phase and the network undergoes fundamental changes to meet this growth. In addition, the network also changes in a technical sense (from tanker trucks to pipeline networks) and the user centers are becoming connected. Interoperability becomes less of an issue now that the basic technologies have been installed and new technologies have to adapt to suit them. Capacity management becomes a central issue for the pipeline network. The supporting role of trucks however serves as helpful flexible back-up capacity in case of shortages or overloads. Concerning responsibility allocation, the framework found that central producers, the transmission pipeline operator, truck distributors, and fuel stations (retail and metering) were heavily involved in the technical operation in the western urban regions of the Netherlands while onsite producers, truck companies, and retailers remained the dominant actors in the Arnhem-Nijmegen center and in more rural areas. Hence reliability was the responsibility of multiple entities, although the pipeline operator played a leading role in the western region. In this snapshot, criticality shifted to interconnectivity and system management and also increasingly to matters of capacity management, while interoperability became less. It was considered the most critical phase, as the entire network was changing due to the switch from onsite production and trucks to central production and pipeline distribution. Central coordination of pipeline operations was deemed necessary to ensure system functioning in such a dynamic setting. How otherwise to coordinate the rapid increases in demand, supply, and network capacity? At the same time, however, trucks played a crucial role in keeping the overall infrastructure flexible. This combination of high criticality and fragmented operational responsibilities led to an organizational structure of vertical integration so as to streamline interactions regarding the operation of the pipeline network while truck delivery allowed for the necessary flexibility for the infrastructure to grow in and cope with the dynamic setting.

In 2050 the roadmap displayed a national hydrogen pipeline network in the west, middle and south of the country, fed by large-scale central facilities based on natural gas, coal and biomass with CCS. This moved truck delivery and onsite production even more into rural areas or other areas further away from hydrogen pipelines. Next to that, slowly but surely production from renewable sources was starting to pick up and enable both more central and decentral hydrogen production. Together with increased demand and number of fuel stations, the hydrogen network became increasingly complex. This was accompanied, however, by a more stable

[176] 'Quasi' because the pipeline network would be operated by a single national operator.

environment (in contrast to the period before) and the advent of a dominant design to which change was likely to be incremental. This shifted focus to the operation of the network rather than the building of the infrastructure. Around 2050 capacity management emerges as the most important technical function for the by then national pipeline network. Safeguarding the balance of the network affects the entire infrastructure operation. Now the pipeline network is built, worries about interconnectivity and system management become considerably less. The more so because the amount of exit points remains limited if compared to the current natural gas network. Interoperability is hardly an issue now that the pipeline network has become the dominant design to which future technologies have to direct themselves. Regarding responsibility allocation, this phase saw that while many entities were still involved, the pipeline operator became the center of operations with truck distributors, onsite and central producers, traders, fuel stations, and the regulator playing a secondary role. Concerning criticality, capacity management became the most urgent, requiring central control to ensure system complementarity, while interconnectivity remained high in criticality and system management and interoperability declined in criticality. As such, overall coordination requirements remained stringent, but shifted to a focus on the network. The combination of high criticality and responsibilities centered in the pipeline operator led to an organizational structure of a lead entity.

With the organizational structures identified, the application of the framework is concluded. Table 7.7 sums up the technological characteristics and organizational structures in the various phases. The Dutch petrol infrastructure is added to give this 'techno-organizational roadmap' a starting point. The table does not only serve as a roadmap summary. It also highlights a number of trends that show how technical characteristics can change during the emergence or build-up of a network and how the organization of infrastructures should change accordingly to ensure reliable operation in each of the phases. Generalizing the results, the table suggest a movement in technical functions from interoperability to interconnectivity and system management to capacity management. In terms of entities involved, we see that in the early stages, onsite producers and truck companies play a dominant role whereas later central producers and pipeline operators start to play a more prominent role. Retailers retain similar levels of involvement throughout. The coordination requirements finally seem to generally increase throughout the course of the roadmap, although the step from 2035 to 2050 may be more about a different nature of criticality (coordination demands) than an actual increase of it. By and large, one can state that reliability concerns move from getting the infrastructure technologies to work in a complementary fashion to managing the use of the network. As such, we also see that the organizational structure changes from one based on multiple autonomous entities that incidentally interact and commonly operate to more vertically integrated structures that eventually focus on the central role of the transmission network operator. The implications of these matters are elaborated in the next chapter.

Table 7.7 A techno-organizational roadmap

Phases	2010	2020	2035	2050
Technical roadmap	National petrol network based on truck delivery	Independent local centers based on on-site hydrogen supported by trucks	Emerging national hydrogen network supported by trucks	National hydrogen pipeline network (trucks only remote)
Involvement entities	Multiple entities roughly equally involved Tasks separable	Two main entities Tasks separable	Multiple entities roughly equally involved Pipeline tasks not separable from rest	Core network entity Pipeline tasks not separable from rest
Coordination requirements	Low criticality Well-established operational routines No regular coordination for planning and tasks	Low criticality Focus on component complementarity Regular coordination for planning, no coordination for tasks	High criticality Coordinate to master changing circumstances; trucks and storage for necessary flexibility	High criticality Complexity instead of dynamic setting Centralization of criticality and control in pipeline operator
Organizational structure	Incidental coordination	Common operation / Incidental coordination	Vertical integration	Lead entity

7.2.2 Reflection on Experiences

The application of the framework to the hydrogen case provides some interesting considerations for the further refinement of the framework. These were mostly a) the idea of a stable versus dynamic setting in which technical operation takes places (resulting also in a debate on the need for flexibility in the face of stringent coordination requirements); b) the presence or absence of a dominant technical design for interoperability; c) the place of development in between planning and facilitation, d) some additional issues with the classification of control mechanisms' scope of control and speed of adjustment, and e) the troubles of integrating such diverse infrastructures as onsite production, trucks, and pipelines. Let us briefly reflect on these experiences.

The hydrogen roadmap showed that situational dynamics needs to be assessed in future applications of the framework. The effect of a rapidly changing, or dynamic, environment on criticality levels and entity responsibilities in our discussion of the hydrogen phases was obvious: it requires flexibility from entities to respond to changes in infrastructure operation that may be at odds with the more stringent conditions for coordination of technical functions like capacity management. In essence, a dynamic setting is one of the circumstances that would require flexibility we asked about in chapter 4.1.3.2. The effect of a dynamic setting on coordination requirements is similar to other infrastructure features although it is not an infrastructure feature as such, but a situational feature that affects coordination requirements just the same. What is still difficult to estimate is how a dynamic or stable setting affects criticality. On the one hand, flexibility is best ensured by autonomous entities that can quickly adapt to changing circumstances, because they are not caught in a web of common operation responsibilities. On the other hand, managing a rapid succession of new entry and exit points in a pipeline network that aims to deliver hydrogen efficiently and effectively throughout a country might require some central guidance to generate an optimal design. In any case, by considering dynamism as a situational feature that might require flexibility, it can be brought into the framework as an additional feature. In a way, this allows bringing in a dynamic aspect into a static snapshot. Though this may seem like 'cheating', one may also argue that even at a specific moment in time, entities are aware of the environment around them and adjust their behaviour accordingly.

In a similar fashion, the concept of dominant design seems attached to the idea of routines and experiences we discussed in chapter 5. The presence of a dominant design acts as a stabilizing factor to which further technical changes are incremental or additional, making radical changes less likely. This allows entities to become familiar with certain operational procedures without the hassle of continuously learning how to deal with new core technologies, which may necessitate new coordination patterns among entities. A dominant design hence allows coordination between certain entities to become routine and predictable. This in turn is likely to ease interaction between them and lessen risks for failure. Of course, complacency and false expectations might be the downside of this. In the end, the roadmap to hydrogen has shown that the framework needs to take the presence or absence of a dominant design on board as a feature.

Concerning the need to construct infrastructure assets such as pipelines between their planning and usage / facilitation, it seems justified to either add the notion of development next to the facilitation and planning of interconnection and strategic capacity management's planning. The speed of adjustment of capacity allocation (medium term) seems to capture this characteristic nicely. It is interesting to note that the concept of development did not appear as an obvious issue in the discussion of the three energy vectors in chapter 5. The roadmap to hydrogen, however, highlighted clearly that the planning in one stage would turn into development in the next.

Regarding classification of control mechanisms, the 2020 snapshot showed three stand-alone local networks that were not interconnected through a transmission network. How to classify them in terms of scope? According to the framework, the local network should be considered a system, because it is not a mere component nor is it connected to a larger system by a backbone. Yet, in terms of scale, this scoping as a system is misleading. The local system simply does not represent the typical idea of a system as most would envision it: a large national network interconnected with other national and regional networks. As a consequence, we would envision more central coordination than might be required for the stand-alone system. Moreover, how to interpret the fact that the local user centers are related in the sense that they together provide hydrogen coverage in the Netherlands and must comply with the same standards? Another example would be how to classify a national hydrogen infrastructure based solely on onsite facilities? There is no physical connection, but together they may facilitate nationwide coverage. New classifications of scopes of control that encompass these examples would be welcome. Alternatively, the current definition of subsystems should include local systems whose entities coordinate with each other to provide infrastructure services without actual physical linkages connecting them.

Regarding the troubles of integrating such diverse networks as the western pipeline-truck network with that of the onsite-truck networks existing in other parts of the country into one organizational structure for the overall infrastructure, two important lessons should be taken on board in future applications of the framework. First, the framework should be applied to a single network at a time if an infrastructure knows two equally dominant networks (two transmission networks). Second, to know whether that is the case, we need to first establish whether or not one network is dominating operation. In our 2035 hydrogen infrastructure this was both the case. In the west of the Netherlands hydrogen was supplied via the pipeline network while truck delivery acted as local subsystems to it. A focus upon pipelines as dominant is hence justifiable. However, the roles of trucks in the onsite-truck networks in the east of the country and the role of pipelines in the west are very similar. Hence it seems best to treat them as separately organized networks that combined operate the overall infrastructure, but that each require their own organizational structure.

7.3 Conclusion

This chapter applied the framework for alignment to the case of a transition to hydrogen as a motor fuel in the Netherlands. The objectives were to properly illustrate the application of the framework on a future case in order to see what insights could be gained and to 'learn by doing' in order to refine the framework further. The roadmap of a transition to hydrogen as a motor fuel in the Netherlands developed by the Energy research Center of the Netherlands (Smit et al. 2007; De Groot et al. 2005) for the European Union's (EU) HyWays project was taken as the guideline. The application of the framework on the Dutch hydrogen case provided some interesting results. It highlighted the changing organizational requirements of the hydrogen infrastructures during its build-up, moving from more bottom-up structures in which autonomous entities incidentally coordinate and commonly operate to more vertically integrated structures that eventually show a leading role of the pipeline operator. It also highlighted in more detail the alterations in the involvement of entities that moved from onsite producers and truck companies to central producers and the pipeline operator, while that of retailers remained largely the same throughout, and the movement of criticality in the technical functions from interoperability to interconnectivity and system management to capacity management. In other words, the illustration of the framework on hydrogen showed how reliability concerns shifted from getting the infrastructure technologies to work in a complementary fashion to managing the use and/or operation of the network. In the end, a brief reflection on some experiences showed that there still are sufficient matters to improve when it comes to refining the framework, but that there are possibilities to do so. Five matters were discussed: the effect of stable and dynamic environments on criticality of technical functions, the presence or absence of a dominant technical design for interoperability, the place of development in between planning and facilitation, some additional issues with the classification of control mechanisms, and the troubles of integrating such diverse infrastructures as onsite production, trucks, and pipelines.

Conclusion

8. Maintaining Reliability in Energy Transitions

We started this research by stating that ensuring reliability in energy infrastructures has a technical and an organizational dimension and that these are related. We then noted that the transition to sustainability implies a series of technical changes that may require new organizational structures to ensure reliability. It hence was important to identify what the organizational requirements of new renewable energy systems were. Noting the absence of the means to do so, the objective of the research became to capture the relationship under study and the complexity of the topic in a simple yet effective manner and to develop and illustrate a framework that is able to translate the technological characteristics of future renewable energy infrastructures into complementary organizational structures. It is now time to see in how far we have succeeded. In other words, are we now able to establish which organizational structures are required for the reliable operation of future renewable energy infrastructures? To answer, this chapter reflects upon the framework developed and the insights gained from its application, points out future directions for further research, and highlights the practical relevance of the framework for sector entities and policy makers preparing for a transition to renewable energy.

8.1 Reflection and Future Research Directions

The framework of alignment has come a long way since its inception in chapter 4. Its exploration on the current energy vectors of electricity, natural gas, petrol and its illustration on the case of a transition to the use of hydrogen as a motor fuel in the Netherlands highlighted many issues to be considered. Let us therefore summarize it and assess its strengths and weaknesses before pointing out possibilities for future research.

8.1.1 Assessment of the Framework for Alignment

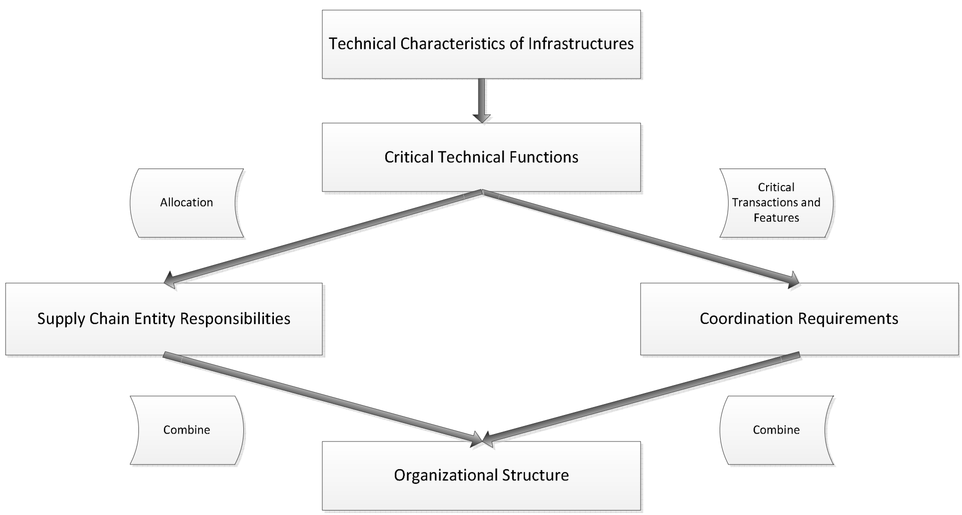
Four steps form the heart of the framework. The first identifies the issues pertaining to the so-called technical functions of interoperability, interconnectivity, capacity management, and system management (and their several subcategories) that energy infrastructure entities have to deal with in order to ensure complementary operation. The four technical functions came from earlier studies regarding the relationship between the degree of coherence between the technical and institutional dimension of infrastructures on overall system performance (Finger et al. 2006). The technical functions were chosen as the focus because they represent those aspects of technical operation that involve and may affect coordination among infrastructure entities instead of the functioning of the technical assets or artifacts themselves which are generally an entity's internal concern. As such, their adequate operation is deemed related to organizational structures. Interoperability focuses on the "mutual interactions between network elements" (Finger et al. 2006, 11-12) such as the complementarity between energy sources/carriers and delivery systems, e.g. voltage levels and electricity wires, or energy characteristics and application requirements, e.g.

natural gas quality and domestic boilers. Interconnection deals with the "physical linkages of different networks that perform similar or complementary tasks" (Finger et al. 2006, 11-12). This includes facilitating the connections between local distribution and national and continental transmission networks and planning for system additions. Capacity management concerns the allocation of "scarce network capacity to certain users or appliances" (Finger et al. 2006, 11-12). Issues pertain to the operational balancing, unit commitment and capacity utilization, maintenance scheduling, and the long-term planning of network and production capacity (Künneke and Finger 2007, 310-311). Finally, system management "pertains to the question of how the overall system (e.g. the flow between the various nodes and links) is being managed and how the quality of service is safeguarded" (Finger et al. 2006, 11-12). This entails mostly aligning production with consumption and ensuring that the energy system is able to adapt to changing conditions. The four technical functions not only pave the road from technology to organization, but also help us to focus on a few key variables, i.e. relevant operational tasks for entities in an energy infrastructure, instead of the plethora of technologies involved. The first step ended with the control mechanisms necessary for the facilitation of the technical functions, such as codes and standards for interoperability or an operations control room for capacity management.

After the issues pertaining to the technical functions have been identified for an energy infrastructure, steps two and three identify the responsible entities for each of the functions and assess the nature of the coordination required between them. These steps are necessary to identify the two key aspects of organizational structures: the actors involved in the organization of a particular transaction or process (who does what, when, and how; and how many) and the nature of their interaction (on a hierarchical-horizontal scale). For the allocation of responsibilities, the entities operating the supply chain – sources, generation, trade, transmission, storage, distribution, metering, retail, consumer, and regulator – were considered. The responsibilities of the current and past (pre-liberalization) entities in the operation of electricity, natural gas, and petrol systems provided a helpful guide in allocating the functions of a future hydrogen infrastructure. Once all critical technical functions were mapped, an overall picture emerges that gives us insights on which entities are involved and which not, which entities are key and which relevant to a lesser extent, and what amount of representatives of a particular entity are involved per critical technical function. For assessing the nature of interaction or coordination required, we moved from technical functions and their control mechanisms to classifying the latter in terms of scope of control and speed of adjustment whose categories were linked to transactional characteristics as posited by transaction cost economics. This allowed us to move further towards so-called modes of organization that represented both the degree of central or decentral coordination requirements and the coordinative structures necessary to address them. In addition, we identified a number of infrastructure and situational features that affected the operation of control mechanism and, in turn, their coordination requirements: complexity of the network, intensity of network traffic, the interdependence of network parts, the flexibility of entities, the dynamic environment in which operations take place, and the presence or absence of routines and dominant designs. These were used to reassess the criticality or coordination requirements of the control mechanisms. It is here where the gap between the technical and social or organizational dimension of socio-technical systems is truly bridged.

Finally, the results of steps two and three are put together to come to the required overall organizational structure. This occurred by combining the entities involved and the coordination requirements among them per technical function and then combining the organizational structures of the four technical functions. Regarding the former, in order to avoid the immense complexity of all possible combinations, we simplified the allocation of responsibilities into categories of whether there exists an entity that is significantly more involved than others or whether multiple entities are roughly equally involved in the facilitation of a technical function and we simplified the criticality of technical functions into strong and weak (central and decentral coordination requirements). This allowed us to link the results to the four ideal-type combinations of organizational structures identified in chapter 2: vertical integration, core entity, common operation, and incidental coordination. Concerning the latter, the aggregate of the structures of all four technical functions presented the overall organizational structure required for reliable operation. To deal with the complexity of the aggregate, we graphically represented all connections in one supply chain overview on the one hand, while adhering to the following logic for putting the overall organizational structure together on the other: those entities charged with the critical technical functions that require central coordination should become the core entities in the overall infrastructure and those that deal with less critical technical functions may be vertically integrated with it, separated from it, or even be completely autonomous, depending on the degree of central coordination required. In other words, we basically looked at the more important entities and functions involved (entities with many responsibilities and functions that require central coordination) and move from there.

Figure 8.1 A framework for alignment



With the framework for alignment summarized, it is time to assess its possibilities and impediments at the hand of its four steps.

Looking at the first step, the focus on technical functions instead of assets has proven itself in the contemporary Dutch energy cases and the future transition to hydrogen as a useful tool to focus on and dissect those aspects of operations that are relevant to the complementary functioning of all chain components. In other words, the critical technical functions proved a good starting point to unravel the complexity of the technical characteristics of future energy systems and helped to focus on those relevant for organizational structures and reliability. On a negative note, one might mention the neglect of development issues in between the planning and facilitation issues that characterize the subdivisions of the technical functions. More fundamentally, the framework in general seems to be attuned to a more mechanical operation of infrastructures; it remains to be seen how it will manage to incorporate the information management that smart grids would require, for example. How to incorporate that into the overall organizational structure? Should it be treated as a fifth technical function or as a feature that enables to operate central systems more decentrally? Or is ICT better understood as a technological characteristic of energy infrastructures that shapes the supply chain and its operation in the first place, determining mechanical operation to which the framework is applied?

The allocation of technical functions to the appropriate entities proved to be the next logical step in identifying the first of the two aspects of organizational structures. Allocating operational responsibility to entities in the hydrogen case was largely based upon comparison with current and past experiences and task divisions among the various supply chain entities (sources, production, trade, transmission, storage, distribution, metering, retail, consumption, and regulators). While these insights were very helpful, it remains somewhat questionable as to how far they can be applied to the more decentral nature of some future renewable energy systems. Even the decentral networks of the 19th century might not capture the scope and decentral nature of solar energy, for example. Positioning consumers as prosumers alters the one-way direction of the supply chain (as do central and onsite hydrogen production) and make distribution network companies the nexus where centrally and decentrally produced energy meets. This would require restructuring the supply chain as one moving from central production and transmission to industrial users and distribution and from households to distribution after which it moves from distribution to a number of other consumers (households and perhaps some smaller industries).

Assessing the coordination requirements for the reliable facilitation of a technical function is perhaps the most disputable step of the four. Most of the problematic experiences of chapters 5 and 7 relate to this step. Two apparent shortcomings lie in the sometimes difficult measurement of the speed of adjustment and classification of the scope of control of control mechanisms and the central role of capacity management in establishing central control needs (only operational balancing seems to require systemic immediate action). The major issue, however, was how to weigh the effect of infrastructure and situational features on control mechanisms. This was perhaps most clearly illustrated by the fact that the literature on NAT stipulated the opposite relationship between complexity and coordination requirements from Künneke et al. (although this could be explained by a difference in focus). Similarly disputable issues included the effect of a stable versus dynamic setting in which technical operation takes place, the need for flexibility (to adapt to technical changes) in the face of stringent coordination requirements, the role of experience, routines, and dominant designs as a factor in coordination, the intensity of network traffic, and the degree of interdependence or coupledness between network segments; how do they affect criticality / coordination requirements? This is simply not an exact science. While they have been addressed and incorporated into the framework, the core challenge has not: they leave many possibilities open to interpretation regarding how they affect the classifications of scope of control and speed of adjustment of control mechanisms. The reason for these troubles seem to stem from the fact that while a focus on control mechanisms' scope of control and speed of adjustment as a way of classifying them with regard to their coordination requirements basically emphasises preventing failures from occurring, the above-mentioned features rather concern the consequences of a failure.

The last step brings both aspects of organizational structures together. However, it does so by simplifying the variety of possible organizational structures into four ideal types. On the one hand, one can criticize this choice for ignoring the many intermediary possibilities. On the other hand, streamlining the possible outcomes helps us to discuss them. It is more imaginative to present a resulting organizational structure as being one of the four ideal types and then mentioning the deviations from it, rather than vaguely describing the same without any clear reference point. In other words, using ideal types helps to clarify organizational requirements. What could be improved, however, is the number of ideal-types. There is always the possibility of adding a new category to the matrix: are one, two, or three or more entities involved and is criticality low, medium, or high? Though the application to the hydrogen roadmap didn't seem to require more classifications in terms of criticality, the option of 'two entities roughly equally involved' does seem distinct from 'one or many' and may be useful to add. Another issue is combining the four organizational structures of the four technical functions into one overall structure. The graphic depiction of the supply chain and the coordination links per function among entities may help in some cases, but the more complex cases seem to create a graph just as complex. The troubles of integrating such diverse infrastructures as onsite production, trucks, and pipelines in the 2035 hydrogen snapshot are an example of this. The logic adhered to in order to unravel the complexity seems a good starting point, but cannot hide the fact that it again simplifies matters.

To conclude, the framework for alignment as presented and applied above seems to have largely established the means to express the technological characteristics of future renewable energy infrastructures in terms of their organizational requirements in light of ensuring reliability. While it might have its quirks during application and there is room for improvement, in the end the framework succeeds in capturing the most important operational aspects of future renewable energy systems using a few key concepts. It also allows for methodically investigating the entities involved and their relationship and establishing the required organizational structure in an orderly fashion. At the very least, it presents the tools or guidelines necessary to undertake the effort and dissect such complex systems as future renewable energy infrastructures into understandable pieces. Hence the framework appears to provide a useful starting point for further exploration of the relationship between the technical and social dimension of energy infrastructures. However, while the framework may have addressed the research question and fulfill the objective of this research, one should not forget that in essence it only represents a hypothesis of how we may proceed to investigate what organizational requirements future energy systems may have. The explorative nature of the research implies that further testing of the framework is still very much required before a theory on the relationship under study can be established that we may utilize with a certain degree of confidence. This research only represents a first step towards such a goal.

8.1.2 Future Research Directions

So where do we go from here? Two avenues present themselves: first, we can improve the framework further, a deepening; second, we can extend the framework, a widening.

Regarding the deepening, basically all four steps of the framework and the effect of the various features that affect criticality can be specified more precisely. Are there any aspects missing from the critical technical functions identified? Can the allocation of functions be done in more detail, i.e. resulting in a better distinction of roles? How could we improve upon the classifications of speed and scope? What is the exact effect of the many features' coordination requirements? What could we learn from various degrees of unbundling? How could we improve the final step towards one overall organizational structure? Are more organizational ideal-types distinguishable? Might we, for example, distinguish more accurate structures if we differentiate between one, few, and many entities involved, plus high, medium, and low criticality? What might we learn from applying the framework to more cases, i.e. other new renewable energy systems or even non-energy infrastructures? How might ICT affect infrastructure operations? Finally, the organizational requirements sought in this research / by the framework are intended for the infrastructure as a whole; why not try to see what they might need to be between two or more specific entities? There is plenty of work still to be done.

Concerning the widening, one possibility is to extend the organizational structures of infrastructures to the broader institutional arrangements that may be needed to guide entity behavior. We saw already in chapter 2 that institutions such as rules and regulations enable and constrain actor behavior. Indeed, the organizational structure of an infrastructure does not exist in a void, but is supported by institutional arrangements that set the boundary conditions and incentive structures under which infrastructure entities operate. The addition of institutional arrangements, however, is not considered in the framework. But why not make this additional step towards supportive institutional arrangements in the framework once one has managed to find an organizational structure for the overall infrastructure?

Let us briefly explore such an addition by taking some earlier works on coherence as a point of departure. Arentsen and Künneke (2003) and Finger and

Künneke (2006; 2007; 2008) identify a number of institutional aspects using Williamson's four layer model (2000) and categorize them into three ideal types: the public property, public utility, and commodity model. As such, they classify informal institutions based on whether the dominant policy focus is public dominance, service or competition (layer 1); formal institutions based on whether ownership, the level of vertical integration, regulatory framework, and market structure are public or private, sector specific or competition policy, or a regulated monopoly, oligopoly or competitive market respectively (layer 2); mode of governance based on whether emphasis is on political control or shareholder profits (layer 3); and resource allocation is based on whether the allocation mechanism is regulated tariffs or market prices (layer 4).[177] The result of their efforts is summarized in Table 8.1 below. In this research, we would be especially interested in the type of institutional arrangements of the second layer. These are the formal rules that shape the political-economic environment in which infrastructure entities operate and which shape their behaviour (as discussed in chapter 2.2.2).

The link between organizational structures and institutional arrangements as formal rules is the factor of vertical integration that exists in both. As such, 'public property' type suits the vertical integrated structure; the 'public utility' type matches the lead organizational structure; and the 'commodity model' type is complementary to the decentral organization with incidental coordination. For the sake of completeness, we have added a fourth institutional arrangement ideal-type that would suit the organizational structure of 'common operation'. It is added in Table 8.1 below. However, such a link is very precarious. Whereas technical operation might require different degrees of centralized control, the level of vertical integration in institutional arrangements is set by economic, rather than technical, considerations along the line of transaction cost economics and non-technical economics of vertical integration. In turn, these three classifications are not based upon technological characteristics of infrastructures, nor do they embody the suggested ideal-type of institutional arrangements for them. They are merely a rough approximation of institutional arrangements that in practice tend to accompany various degrees of vertical integration in the energy sector.

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[177] The rest is rather self-evident: a private mode of organization implies private ownership, a horizontal organizational structure, competition regulation and a competitive market setting while a public mode of organization equals public ownership, vertical integration, sector specific regulation and a monopolistic market structure. Surrounding a private approach is a general focus on competition, profitability, an international and local orientation, shareholder control and market prices while a public approach is embedded in a sphere of public values, political controllability, a national orientation, government control and regulated tariffs (Künneke and Fens 2006).

Table 8.1 Ideal-type institutional arrangements for degrees of vertical integration

Institutional Arrangements	**Public property**	**Public utility**	**Common operation**	**Commodity model**
Embeddedness / dominant policy focus	Public dominance / resource policy, producer oriented	Public service / market failure, network oriented	Competition, consumer orientation	Competition, market orientation
Formal rules / Political-economic organization				
Ownership	Public	Public network, private production and retail	Private, tasks delegated	Private
Vertical integration	Complete chain	Network, but production and retail unbundled	Coordinating entities	Autonomous entities
Regulatory framework	Sector specific; controlled access and limited number of actors	Sector specific; controlled access and limited number of actors	Competition policy; open access and many actors	Competition policy; open access and many actors
Market structure	State monopoly	Regulated monopoly	Regulated market	Competitive market
Governance emphasis	Political control, maximization of state revenues, national welfare and prosperity	Political control, reasonable consumer tariffs and selective services, public service obligations	Shareholder profit, static and dynamic efficiency, coordinative structures and mutual dependence	Shareholders profit, static and dynamic efficiency, competitive economic structures and allocative efficiency
Resource allocation mechanism	Regulated tariffs	Regulated tariffs	Competitive market prices	Competitive market prices

Source: adapted from Künneke and Finger 2007, 323.

Another possibility is utilizing the framework for alignment in studies on the co-evolution between institutions and technologies and research into the functioning of socio-technical regimes. By bridging the gap between the technical and organizational dimension of infrastructures, albeit in a one-way fashion, we have furthered our understanding of the relationship between both dimensions. These insights are of great value to studies on the co-evolution of institutions and technologies (Nelson 1994; Saviotti 2005; Foxon 2008; Bolton and Foxon 2011) and the unraveling of the socio-technical regime's workings in socio-technical systems literature (Geels 2002; Verbong and Geels 2007; Weijnen and Bouwmans 2006). The added value of the framework in their light is that it allows pinpointing whether action and reaction are strongly or weakly related. So far, investigations have been mostly centered on establishing that changes in one dimension have led to subsequent changes in another. In his 1994 article, Nelson writes for example that "a new technology develops along a relatively standard track from the time it is born, to its maturity, and that firm and industry structure 'co-evolve' with the technology [and that] the development of institutions [occurs] in response to changing economic conditions, incentives and pressures" (Nelson 1994, 49). Yet there is no way of establishing whether the reactionary changes produce a complementary outcome. The introduction of a new technology in socio-technical systems, for example, like the move from hydrogen trucks to hydrogen pipelines, might produce a change in organizational structure that differs from the desired outcome based on the framework. As we saw in chapter 2, this is related to the many forces that may affect changes in organizational structures, because of which these structures may not change according to technical requirements, but economic, social, and political ones. In other words, without the framework, how can we know whether the resulting organizational structure is suited to the technical changes? If we would be able to know, however, more detailed studies on the presence or absence of co-evolution in socio-technical systems would be possible. Then we could, for example, revisit the historical overview of chapter 3.2 and see whether technical changes or other forces have driven organizational changes. Of course, the frameworks and theories on co-evolution and socio-technical systems would need to adopt the definitions of the framework in order to proceed, i.e. focus on the changes in critical technical functions that a new technology might bring.

8.2 Practical Implications and Relevance

The framework for alignment is not only useful to scientists trying to understand the organizational requirements of technical changes in energy infrastructures in light of reliability. It also harbours practical insights for the various entities involved in daily operations and for policy makers facilitating a transition towards sustainability. Because the framework helps to set up an organizational roadmap, sector entities can use it as a tool to define their changing role and responsibilities towards reliability over time, aiding them in making investment decisions. At the same time, the framework helps policy makers to understand the broader implications of technical changes in energy infrastructures and subsequently shape a policy that facilitates the co-development of the technical and organizational dimensions. Let us now take a closer look at how they may utilize the framework to their advantage.

8.2.1 How Infrastructure Entities May Benefit from the Framework

In the previous chapter we saw that the reliable operation of new renewable energy systems may have different organizational requirements at various stages of development. The organizational structures we identified, however, represented a general picture for the entire infrastructure. As such, it remains somewhat unclear what they imply in terms of precise changes for individual entities. What consequences do the technical changes have on entities' responsibilities and how will coordination between specific entities change as a result? The entities operating the hydrogen infrastructure may be expected to show a great variety in responsibilities, partners, and ways of interaction in each of the three hydrogen snapshots. Whereas in 2020 few entities are responsible for technical operation, in 2035 and 2050 many, if not all, were actively involved some way or another. Whereas decentralized operation was sufficient in 2020, more centralized organizational structures were required in 2035 and 2050 to guarantee reliable operation. Moreover, the entities involved in interoperability, interconnection, capacity management, and system management changed considerably over time. Let us therefore take a closer look at the most prominent hydrogen entities throughout the roadmap's stages (onsite and central producers, truck delivery and pipeline network companies, and fuel stations / retailers) by focusing on the more detailed results of steps one, two, and three of the framework. This will illustrate how infrastructure entities may utilize the framework for alignment to envision their future responsibilities, point out the entities with which they will have much or few interaction, and determine the nature of that interaction.

In the beginning, onsite producers are involved in all four technical functions while later they are no longer involved in interconnection and capacity management (2035 and 2050), although they retain some responsibility regarding hydrogen production standards (interoperability) and satisfying rural or local demand (system management). At first, they are the cornerstones of the early hydrogen user centers as local production islands, but ultimately their role is taken over by central production facilities once demand for hydrogen has become large enough. Then onsite production becomes a rural phenomenon. Onsite producers coordinate their activities with truck distributors and retailers throughout the roadmap despite the change in location from urban centers to rural areas. It remains to be seen, however, in how far onsite producers function more as self-producing retail outlets or whether they retain a central role in rural hydrogen centers. In short, while they represent an important aspect of hydrogen's upstream in the early stages, their function in the whole is increasingly marginalized. This might not be dramatic technically, but from an economic or business perspective it will be of great concern to them. Will they manage to stay in business?

Central producers are non-existent in 2020, feed a regional market by 2035, and produce for nation-wide hydrogen coverage by 2050. At the same time, they switch sources from natural gas to increasing levels of coal and biomass with CCS and finally renewables (wind). Technically, central producers have no responsibility for interconnection, but they are involved in setting and complying with hydrogen standards in 2035 and 2050 (interoperability). They are also involved in capacity management in 2035 and 2050 and especially system management in 2035 where they have to replace onsite production without adversely affecting reliability. Operation-wise, central producers coordinate mostly and almost exclusively with the transmission operator. Economically, retailers and traders play an important role in buying hydrogen from producers. Perhaps most interesting is that despite their important role in hydrogen markets, from an operational point of view producers are autonomous entities that tend to follow the lead of the pipeline operator regarding production volumes. For central producers, the roadmap's move from regional centers to a national hydrogen network harbors great promise, because the growing network will allow them to reach retail outlets across the country. On the downside, they might lose their regional production monopoly to competitors across the country.

Hydrogen truck delivery follows a similar route throughout the stages of the roadmap as onsite production, but appears to retain a higher operational relevance a bit longer. In 2020, trucks are involved in all four critical technical functions, though most importantly for connecting onsite production with fuel stations further away from natural gas pipelines. Eventually, they are less concerned with interoperability and capacity management of the overall system, but they remain important for interconnection and system management in that they facilitate hydrogen delivery to urban networks (2035) and remote regions (2050) as an extension of the pipeline network. They also play a supportive role as emergency back-up delivery in case of pipeline failure in both snapshots. Truck companies will need to coordinate with onsite producers and retailers at first and with transmission companies and retailers later on (though remote hydrogen user centers like Arnhem-Nijmegen in 2035 may keep onsite producers relevant for a while longer). Economically, trucks play an important role in stimulating demand in areas where onsite production is cumbersome and may be a cost-efficient option for low-volume short-distance hydrogen delivery. Truck companies are likely to be rather autonomous entities throughout the roadmap, contracting when necessary rather than functioning in any sort of hierarchy of operational control, even though they are heavily involved with the pipeline operator by 2035. They will however need to find a way to cope with their diminishing prominence and necessity.

The hydrogen transmission pipeline operator sees the opposite development of hydrogen truck companies. Starting off as non-existent, even with the existence of industrial hydrogen pipelines, it becomes the center of attention for all four technical functions by 2050. While its reach may still be limited to the western region of the Netherlands and many other actors remain important for the maintenance of reliability in 2035, the advent of the national transmission grid and the absence of distribution pipeline grids makes it the dominant actor in interconnection and capacity management, while staying an important actor in interoperability and system management until 2050. The TSO deals with a host of other entities from 2035 onward; producers, traders, truck companies, retailers / meterers, and the regulator. Its central role is not expected to manifest itself immediately as in 2035 intensive coordination among all entities is likely to be required to facilitate the co-development of production, network, and retail in various more or less interconnected hydrogen regions. In time however, the TSO increasingly takes central control as the pipeline network starts to cover the country. In other words, it becomes the nexus for technical operation. However, it is important to note that the nature of hydrogen gas in terms of transport flow regulation and storage possibilities allows for a certain degree of unbundling of production and retail from the hydrogen network. The TSO thus will act more as a lead entity in operations.

Finally, retail or fuel stations appear to play a fairly consistent role throughout the roadmap. This stems from their position as meterers of demand; data to which the rest of the sector adheres to when determining production levels and commitment of distribution means. Because of this function, fuel stations are continuously involved in system management and in pipeline based capacity management. Interconnection, however, is not their responsibility, nor is interoperability except perhaps for ensuring proper storage standards. Fuel stations play a rather autonomous role in the technical operation. Truck companies and pipeline operators are their main partners, but coordination is likely to involve only incidental delivery contracts with occasional emergency delivery. The technical role of demand data provider is likely not matched by a dominant economic role, if petrol is an indication. Some stations may be owned and operated by hydrogen producers, some may be independently operated. Either way, they are not likely to shape the market as much as producers, the network operator, or even traders. Over the course of the roadmap, fuel stations increase in number first in cities and along major highways, and then in more rural areas. Their nature also changes from an onsite facility – hydrogen fuel station hybrid to that of being a fuel station only in urban areas, while some hybrid functions may remain in rural areas.

Such an overview that is based on the first, second, and third step of the framework helps picture the future role (the position of an entity in overall operational hierarchy) and responsibility (operational tasks in terms of the four technical functions) of individual entities and may in turn assist them in making investment decisions or otherwise serve preparations. It will be interesting to study other renewable systems like solar, wind, biomass etc. and find out what entities and cooperation patterns they might involve. Especially interesting in this regard will be how this might change existing electricity grid operations, i.e. the entities involved and their interaction. In any case, by taking the results from each of the steps separately and not only focusing on the final outcome, many detailed findings for individual entities may be derived that can be of great value and interest.

8.2.2 What Policy Makers May Learn from the Framework

Having a framework to investigate the organizational requirements of renewable energy systems offers many benefits for policy makers. First, the framework helps policy makers to assess the implications of technical changes on sector reliability and as such assist in maintaining reliability in energy infrastructures. The framework also presents policy makers with a target to aim for, i.e. an idea of which organizational structure needs to be in place (and what outcomes of organizational reform need to be avoided), creates societal awareness on the need for looking at reliability from a socio-technical perspective, and allows policy makers to enhance techno-economic roadmaps with an organizational dimension in order to make better-informed decisions. In the hydrogen case, for example, technical changes between 2020 and 2035 show a shift from a more decentralized to a highly centralized system. This may have a profound effect on reliability if the technical changes were to develop and the organizational changes not. It is likely that the greater the discrepancy between the current and future required organizational structure, the greater the difficulty to achieve those changes and the greater risk for and negative consequences of failure. One could even go further into the implications for the accompanying institutional arrangements in a similar way. In other words, the framework arms policy makers with the means to prepare for future changes instead of leaving them to respond once problems arise.

Second, the framework helps to reflect upon whether current operations are optimal for maintaining reliability. Chapter 5 already showed the possibilities and impediments of utilizing the framework as a means to reflect upon the reliability performance of energy infrastructures by comparing the proposed organizational structure (based on technical operation) with the actual (mostly based on political economic considerations) and debating whether the difference could be related to lower performance. A major obstacle here was the absence of counterfactuals (two Netherlands with two electricity networks with different organizational structures) and the fact that more effort by entities (higher transaction costs) may still lead to similar reliability levels. This implies that transaction costs would need to be carefully calculated to make such a comparison work. Considering the difficulty in quantifying such transaction or coordination costs, especially when it concerns technical operation and not the contractual arrangements of transaction cost economics, such an exercise may be very difficult, if feasible at all. Nevertheless, having the outcome of the framework as a reference point might go a long way in helping to estimate or identify the technical requirements and possibilities for improving operational efficiency.

Third, the framework may help policy makers to estimate the implications of sector reforms on reliability. Despite the fact that the framework moves from technology to organization, this does not necessarily mean it is useless for assessing the effect of organizational changes on reliability. One might study, for example, the actual and intended future organizational structure of an energy infrastructure undergoing reform and contrast this with the framework's insights on the required organizational structures of the technologies in place at both points in time. For example, we might contrast petrol's organizational structure and the required structures for hydrogen with plans for on-going liberalization and unbundling. Are sectoral reforms likely to increase or decrease coherence and reliability? This also links back to the research by de Bruijne or the Künneke et al. regarding the effects of liberalization and unbundling of electricity networks on their performance.

Fourth, the framework also may help policy makers to assess the desirability and feasibility of techno-economic roadmaps in an organizational light. Because introducing new technologies might prove to be considerably easier than changing sector organization, the lengthy and troublesome liberalization and privatization process being a case in point, the notion of organizational lock-in and path-dependency should be included into planning roadmaps towards future sustainable energy systems. Considering that most scenarios and visions limit themselves to the technologies they involve and how best to introduce them to society, the techno-organizational roadmap created by the framework allows for comparing the nature of changes in both roadmaps. The HyWays roadmap, for example, was based on a desirable techno-economic picture in terms of smoothing the market introduction of hydrogen based fuel cell vehicles; but are different hydrogen options or development paths preferable if one considers the major organizational changes required between 2020 and 2035? Moreover, if we consider the decentral alternative roadmap described in chapter 6 in this regard, it seems that lock-ins into non-hierarchical forms of organization might cause the roadmap to alter course towards hydrogen networks remaining decentral until 2050. The central alternative roadmap, in contrast, seems to involve far fewer technical and organizational changes because the central production and pipeline system would be in place from the start. Yet then we must consider the economic costs and high risk of 'starting large'. In the end, one might even take it one step further; what is the effect of adding alignment as a policy objective to the hydrogen build-up?

Nevertheless, there is one thing the framework does not provide: the means to achieve co-development. Knowing which organizational structures match particular technological characteristics of energy infrastructures is one thing, being able to reform sector organization to align it to technical changes (or vice versa) is quite another. We should not forget that for policy makers the issue is to get there, i.e. to co-develop technologies and organization in such a way so as to maintain coherence between them. According to chapter 2.3, maintaining reliability requires a twofold effort by policy makers. On the one hand are the technical assets that simply need to function and that require maintenance. On the other hand is the organizational structure that shapes the possibilities for entities to coordinate for system operation. It was also shown that processes of technical and organizational change are very complex in and of themselves and that both dimensions develop according to their own dynamics and may not necessarily produce a coherent outcome. Hence the question was posed how (and to what extent) policy makers could guide these processes towards co-development? It is important to note here that such a question and the concept of co-development for that matter distract us from the carefully constructed environment in which we have sought to identify what organizational structures new renewable energy systems may require. It takes place in a practical setting that is very complex in terms of the actors and factors involved and one that is also highly dynamic. Moreover, in such a setting an exclusive focus on reliability as a policy goal cannot be assumed and technological characteristics cannot be taken as given, i.e. multiple technical options are likely to be explored at the same time. This creates a number of serious challenges for policy makers.

First, in practice reliability is but one of many objectives that policy makers pursue. We already saw that the IEA and the Dutch government try to balance availability, affordability, reliability, and sustainability concerns. These aims are sometimes complementary and sometimes conflicting, creating trade-offs between them and forcing policy makers to choose. Because pursuing reliability might come at the cost of achieving satisfactory results in other areas, reliability is sought to the extent governments deem sufficient, which may vary greatly across countries. In addition, ensuring reliability costs money. Because ensuring a 100% reliable energy infrastructure might cost a disproportionate sum of money in relation to the benefits reaped by it, policy makers may rather pursue an optimally reliable infrastructure. Where this lies is subject to debate. What is a government ready to accept as minimum requirements? How many minutes a year may electricity or gas blackouts last?[178] It is not the purpose of this study to define where this optimum lies. However, it is important to remember the trade-off it represents.

Second, in practice actors have interests beyond reliability. While the actors are still the various entities as before, they are better perceived as discussed in chapter 2.2.2, i.e. as having their own strategic interests such as profit maximization. As this may run counter to the reliable operation of an infrastructure, policy makers need to ask themselves how they might overcome conflicts of interests in the pursuit of reliability. While actors may sometimes see opportunity and support technical and organizational changes proposed by policy makers for the sake of reliability, at other times they may oppose the introduction of a new technology or organizational reform. Governments may play different roles in dealing with actors in order to get what they want; they may facilitate them, negotiate or bargain with them, and even intervene and coerce them into accepting new technologies and organizational structures (Campbell and Lindberg 1991; Hisschemöller et al. 2006). Of course, even then success is not guaranteed. This depends much on the power endowments that policy makers have vis-à-vis sector actors to implement and enforce their policy.

Third, there are many factors continuously driving technical and organizational change, as we saw earlier in chapter 2 and 3. For example, technical, economic, social, cultural or political developments (Campbell and Lindberg 1991) are continuously calling for governance transformations to adapt institutions to their new environment. The same goes for technologies that are continuously reinvented and adapted to suit new needs. At the same time, developments in one dimension might follow each other in rapid succession, while in another dimension things are relatively stable. The political economic setting of organizational change might be relatively stable despite the introduction of radically new technologies such as smart meters and decentral solar PV possibilities. Hence policy makers need to decide whether to align organization to technologies or vice versa. In addition, they also need to incorporate the speed with which technologies and organization may change or can be changed. While technologies may quickly adapt to suit new environments, sector reorganization may easily involve many years if not decades.

[178] Conceptually however, things are simpler. It is easy to imagine 5 'levels' of reliability. These are the situation in which a network is 0% (not) and 100% (perfectly) reliable, where it is optimally reliable (where effective operation is balanced with efficient investments to let it meet the required standard at the lowest cost; the point of equilibrium because no one would either want to spend more money or risk lower reliability), where the network is underreliable (when reliability is not ensured, but costs are low), and when there is overreliability (when reliability is ensured / high, but the costs do not justify the increased levels (over the targeted level / minimum) of reliability) (CPB 2004, 9).

Finally, whereas policy instruments to develop and deploy new energy technologies and stimulate investment in assets and maintenance abound, instruments to reform sector organization seem to be of a very different nature. The HyLights study by ECN (Ros et al. 2006, 14-32; Jeeninga et al. 2007)[179], for example, identify R&D, investment, and production subsidies, zero or low interest loans and tax exemptions, quota obligations, emission trading and environmental regulation, and public procurement and cooperative private procurement as possible hydrogen policy support models and mechanisms. Such a list presents a good mix of price-driven and quantity-based support, technology specific or generic mechanisms, supply or demand orientations, and mechanisms with a direct or indirect impact on the competitiveness of new hydrogen technologies. Alongside these direct technology-targeted policy instruments, regulation might stimulate sector incumbents (mostly network operator(s)) to invest in renewable sources, capacity, maintenance, process and product innovations, or otherwise try to shape the economic behaviour of infrastructure companies. Questions as to the proper 'institutional arrangements' or 'regulatory incentives' to these ends are frequent topics of research. A typical example would be the report by the CPB (2004) on the role of (regulatory) institutional arrangements as incentives for sector incumbents to invest in technical reliability. In this endeavor, creating high investment and incentives for innovation is equated with success, solving all technical problems.

Changing the organizational structure of energy infrastructures requires very different instruments and is of a rather different order of magnitude; liberalization, privatization, unbundling, regulation, nationalization, vertical integration, etc. are all means to change the overall structure under which entities operate and coordinate. Not surprisingly, while policies to support the development and deployment of new energy technologies are frequently used, the tools to restructure organization are more cautiously used. Sector reorganizations hardly ever are easy. Actors rarely like change, especially if it is of no immediate benefit to them (overall reliability may not be interesting beyond a certain point for actors driven by economic gain), or when it implies a change of actors' roles in the overall technical system (causing much uncertainty and adjustment pains). The general governance structure of a country matters greatly in this respect; planned economies are likely to face considerably less private opposition than liberal democracies where government intervention might be considered unwanted, illegitimate even, by sector entities.

Nevertheless, not all is hopeless. While co-development appears difficult to achieve by design, one should not forget that technologies and institutions frequently do affect each other and that mutual adaptation is continuously ongoing. Insights regarding how institutions may shape technical change and evolution (Saviotti 2005; Nelson and Winter 1982; Dosi and Nelson 1994; Dosi 1982) and how technological change in turn may act as one of the drivers for institutional changes (Campbell and Lindberg 1991; Murmann 2003) are well established scientifically. Yet the number of actors and factors and the complexity of the transformation processes involved allow for a bewildering amount of possibilities. Hence, co-development might very well not

[179] Others distinguish similar sets of policy instruments or packages (Arentsen et al. 2001; Bleischwitz et al. 2010; Foxon et al. 2009).

occur. Indeed, technical and organizational change seems to be inherently unpredictable or evolutionary in nature (Campbell and Lindberg 1991; Campbell 1997, 2004; Murmann 2003; Kallis 2001, 2007a, 2007b; Norgaard 2005; Winder 2005, Winder et al. 2005). The real question then becomes under what conditions a 'co-evolution' or spontaneous co-development may occur, i.e. when will organizational structures adapt to technical changes through market or societal forces and without active design by policy makers?

Looking at our hydrogen case, combined with the comments made above and in chapter 3.2, four general considerations seem highly relevant to set the right conditions for spontaneous co-development. First is the nature of technical change. Incremental changes may not require much organizational change, while radical changes are more likely to do so. However, radical technical changes may incentivize actors to more strongly pursue complementary organizational changes in order to utilize the technologies efficiently and to avoid more grave repercussions (incoherences) from emerging. Second, a stable political-economic or socio-cultural environment for organizational change allows technical changes to outweigh other driving forces for organizational change, resulting in organizational structures more attuned towards reliability considerations. Third is actor support for the proposed technical and organizational changes. If actors oppose organizational reforms towards more integrated or autonomous structures, they may block any change policy makers would like to achieve with an eye on reliability. This seems increasingly likely when organizational changes become more radical. Finally, the means actors possess to support or oppose technical and organizational changes effectively in relation to those of policy makers. This also depends on whether a large or small share of actors expects to benefit and what role the government may legitimately play in effecting changes. To sum up, if the above conditions are favourable, the likelihood of co-evolution is high and the co-development along the lines of a techno-organizational roadmap relatively feasible; otherwise it might be better to pursue another route. In the end, it seems that the combination of conditions for co-evolution and possibilities for design by governments presents us with a paradox. While the situation of co-evolution is unlikely to occur, it creates a setting in which co-development is likely. Yet while the situation of designed alignment is likely to occur, it creates a setting in which co-development is difficult to achieve. Consequently, one cannot help but be somewhat pessimistic about the prospects of co-development. It seems to remain a matter of continuous policy efforts and to result in imperfect adjustments at best. But to end on a positive note, history does show that co-development has by and large occurred in energy infrastructures throughout the last 150 years.

8.3 Conclusion

The objective of this research project was to develop and illustrate a framework that pinpoints the organizational structures required for the reliable operation of future renewable energy infrastructures. To this end, it attempted to capture the complex relationship between the technical and organizational dimension of energy infrastructures with regard to reliability in a simple yet effective manner and proposed a means to find the organizational requirements of the technologies employed in future renewable energy systems in light of reliability. This chapter assessed in how far we have succeeded in meeting this objective by summing up the framework developed and discussing its strengths and weaknesses. The final verdict is that while the framework is able to generate detailed insights on the entities involved in the operation of new renewable energy technologies and the nature of coordination among those entities in its various steps as well as a rough general impression of the overall organizational structure required, there were nonetheless several issues raised during its application that warrant a cautious utilization of the framework. Afterwards, possible directions for future research and practical uses for infrastructure entities and policy makers were pointed out. As for further research, a deepening into solving the quirks and a widening to extend the framework to move from organizational structures to institutional arrangements and to further embed it into socio-technical and co-evolutionary analyses were proposed. In terms of the practical relevance, we noted that the framework helps to enhance roadmaps to future renewable energy systems with an organizational dimension (creating the ability to anticipate and prevent future network failures instead of responding to failures ex post), assists industry entities to sketch their role and responsibilities in future energy systems, and aids policy makers in overseeing the organizational implications of technical choices (stimulating awareness of possible new organizational lock-ins and path-dependencies). This way, policy makers may also make better-informed decisions on facilitating the co-development of technology and organization during socio-technical transitions.

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Summary in Dutch

Een Oog op Betrouwbaarheid; De Organisatorische Vereisten van Toekomstige Hernieuwbare Energiesystemen

De organisatorische vereisten van betrouwbaarheid en de uitdaging van een energietransitie

Het uitgangspunt in dit onderzoek is dat de technische betrouwbaarheid van energie infrastructuren organisatorische vereisten heeft, maar dat deze moeilijk te bepalen zijn en dat de mogelijkheid om deze te bepalen van grote waarde is bij het voorbereiden op toekomstige hernieuwbare energiesystemen. Uit studies blijkt dat betrouwbaarheid in energie infrastructuren niet alleen een technische, maar ook een organisatorische dimensie bezit, en dat beide aan elkaar gerelateerd zijn. Zo menigeen ongeluk in energie infrastructuren dat in eerste instantie lijkt voort te komen uit technische mankementen in pijpleidingen, draden, generatoren, controle apparatuur etc., blijkt bij nadere inspectie in ongeveer 80% van alle gevallen toch te resulteren uit een gebrekkige onderlinge afstemming van verantwoordelijkheden en slechte communicatie en coördinatie tussen de bij de operatie betrokken actoren. Bovendien, terwijl de initiële technische mankementen relatief eenvoudig verholpen hadden kunnen worden, zijn vaak organisatorische obstakels oorzaak daarvan dat deze fouten zich konden verspreiden over het gehele netwerk. Helaas echter missen wij ondanks de realisatie dat betrouwbaarheid organisatorische vereisten heeft nog steeds de middelen om de noodzakelijke organisatiestructuren te bepalen. Hoewel de technische, operationele dimensie en de organisatorische, institutionele dimensie goed bekend zijn, zijn de onderlinge relatie en diens gevolgen voor de betrouwbaarheid van infrastructuren nog steeds onduidelijk. Wanneer noodzaakt bijvoorbeeld de betrouwbare operatie van energiesystemen centrale controle en verticale integratie en wanneer kan men deze overlaten aan autonome actoren die grotendeels onafhankelijk opereren? Dit zorgt voor een dilemma dat een onmiddelijke oplossing eist, gezien de lopende transitie naar hernieuwbare energiesystemen. Deze betekent namelijk een serie van technische veranderingen in energie infrastructuren die mogelijkerwijs geheel nieuwe organisatiestructuren vereisen voor het verzekeren van betrouwbare operatie. Het idee dat vele huizenbezitters straks bijvoorbeeld in staat zijn om de door hun opgewekte zonne-energie in het elektriciteitsnetwerk in te voeren, vereist een nieuwe aanpak van het netwerk om deze 'prosumers' te faciliteren. Het is daarom van groot belang er achter te kunnen komen wat de organisatorische vereisten van hernieuwbare energiesystemen zijn.

In het licht van bovenstaande is het doel van dit onderzoek om de complexe relatie tussen de technische en organisatorische dimensie van energie infrastructuren met betrekking tot diens betrouwbare werking in een simpele en effectieve manier te vangen en een raamwerk te ontwikkelen en illustreren dat in staat is de technologische eigenschappen van toekomstige hernieuwbare energiesystemen om te zetten naar complementaire organisatiestructuren. Daarbij is de centrale vraag hoe men zou kunnen bepalen welke organisatiestructuren noodzakelijk zijn voor het betrouwbaar opereren van toekomstige hernieuwbare energie infrastructuren.

Het onderzoek behelst in essentie het voorstellen van de middelen en het identificeren van enkele algemene richtlijnen waarmee de organisatorische vereisten van toekomstige energiesystemen met betrekking tot betrouwbaarheid gevonden kunnen worden. De wetenschappelijke relevantie van het ontwikkelen van een dergelijk 'raamwerk voor afstemming' betreft het vorderen van ons begrip van de relatie tussen de technologieën en organisatiestructuren in energie infrastructuren, de mogelijkheid de organisatorische vereisten van hernieuwbare energietechnologieën te bepalen en het begrijpen van de rollen en verantwoordelijkheden van verscheidene entiteiten in het faciliteren van betrouwbaarheid in socio-technische systemen. De maatschappelijke relevantie komt voort uit de potentiële toepassingen van het raamwerk: de mogelijkheid om te anticiperen op en voorkomen van toekomstige operationele noodgevallen in plaats van ex-post te reageren, de mogelijkheid voor wetenschappers bestaande technische energietransitiepaden te voorzien van een organisatorische wederhelft (en het stimuleren van bewustwording van de mogelijke organisatorische lock-ins en pad-afhankelijkheden die daaruit volgen), het helpen van beleidsmakers de bredere organisatorische implicaties van technische keuzes te overzien (en hen te helpen beter geïnformeerde keuzes te maken omtrent het faciliteren van socio-technische transities) en het assisteren van bedrijven in de energiesector door het schetsen van hun rollen en verantwoordelijkheden in toekomstige energiesystemen.

De zoektocht naar een raamwerk voor afstemming geschiedt in drie delen. Het eerste deel identificeert het probleem, introduceert de voornaamste concepten en presenteert de huidige status van conceptuele en praktische kennis van het onderwerp. Het tweede deel ontwikkelt het raamwerk voor afstemming en exploreert diens toepassing op de benzine-, aardgas-, en elektriciteitssectoren in Nederland met als doel het verder verfijnen van het raamwerk. Het laatste deel introduceert de casus van een transitie naar het gebruik van waterstof als motor brandstof in Nederland en past het raamwerk daarop toe om zodoende diens gebruik en relevantie te illustreren. De conclusie zal uiteindelijk bespreken in hoeverre dit onderzoek er in is geslaagd het gewenste raamwerk te ontwikkelen en zal kort enkele mogelijkheden voor verder onderzoek en praktische applicaties aanduiden.

Betrouwbaarheid in socio-technische systemen

Het vinden van de organisatorische vereisten van de technische operatie van energie infrastructuren begint met het begrijpen van de concepten en hun relatie, het definiëren van het probleem, en het verstrekken van verwachtingen. Hiertoe is literatuuronderzoek naar betrouwbaarheid in socio-technische systemen enerzijds en energietransities en de ontwikkeling van infrastructuren anderzijds ondernomen.

De constatering dat betrouwbaarheid organisatorische vereisten heeft, noodzaakt het definiëren van betrouwbaarheid in een socio-technische context in plaats van een exclusief technische. Doorgaans is betrouwbaarheid gedefinieerd als het vermogen van een energie systeem om een product (of dienst) te leveren via een netwerk zonder onderbreking en zonder verslechtering van de kwaliteit (CPB 2004, 18), dat wil zeggen de mogelijkheid om de door de klant gewenste kwantiteit en kwaliteit van energie te leveren wanneer het nodig is (McCarthy et al. 2007, 2153). Hierbij ligt de focus op de technologieën, de tastbare artefacten in de keten van een energie infrastructuur zoals pijpleidingen, kabels, overslagstations, generatoren, besturingssystemen, etc., die betrokken zijn bij de operatie van een energiesysteem. Organisatorisch gezien dient echter de aandacht uit te gaan naar de interactie tussen de entiteiten[180] van infrastructuren in het beheer van dagelijkse activiteiten (opgesplitst in technische componenten als bronnen, opwekking, groothandel, transport, opslag, distributie, meting, detailhandel, consumenten en toezichthouders). De uitvoering geschiedt immers door mensen en bedrijven die tevens in een bepaalde institutionele omgeving opereren. Speciale focus ligt daarbij op organisatiestructuren die de mogelijkheden van entiteiten voor het opereren van de infrastructuur bepalen. Twee aspecten spelen hierbij een belangrijke rol: wat zijn de verantwoordelijkheden van entiteiten (wie doet wat, wanneer en hoe) en wat is de aard van hun interactie (hiërarchisch of horizontaal)? Doorgaans worden organisatiestructuren onderscheiden op basis van de mate van verticale integratie. In dit onderzoek worden vier ideaaltypen onderscheiden die speciaal gericht zijn op technische operaties: 'verticale integratie', 'leidende entiteit', 'gemeenschappelijke operatie' en 'incidentele coördinatie'.[181] Gezien de relatie tussen beide dimensies benadrukt het onderzoek hoe een bepaalde mate van coherentie tussen beide dimensies bijdraagt aan het betrouwbaar presteren van infrastructuren (Finger, Künneke, en Groenewegen 2005-2010). Als de verdeling en grenzen van de technische en organisatorische verantwoordelijkheden overlappen en de technische en organisatorische coördinatiemechanismen overeenkomen dan mag betrouwbare operatie als waarschijnlijker worden verwacht.

Toekomstige hernieuwbare energiesystemen en de transitie daartoe vormen een uitdaging voor het betrouwbaar functioneren van energiesystemen. In essentie

[180] De term 'entiteiten' wordt gebruikt in plaats van 'actoren' of 'organisaties' omdat wij hen behandelen als de 'nodes and links' van technische systemen, waar ieder zijn taak dient uit te voeren en een bepaalde rol speelt in het geheel. Ze worden dus niet gezien als actoren met autonome interesses, i.e. als hebbende economische preferenties die tegengesteld kunnen zijn aan betrouwbaarheidsoverwegingen. Dergelijke overwegingen horen niet deel uit te maken van een poging de organisatorische vereisten van de technische operatie van hernieuwbare energiesystemen te vinden.

[181] 'Verticale integratie' impliceert dat infrastructuren worden georganiseerd door een enkele entiteit die alle technische operaties van productie tot transport, distributie en retail top-down coördineert vanuit een centrale meldkamer. In de 'leidende entiteit'-structuur bezitten verscheidene entiteiten de formele verantwoordelijkheid over een deel van de technische operatie, maar treedt een enkele entiteit (vaak de transmissiesysteembeheerder) op als leidinggevende voor belangrijke coördinatie-activiteiten. 'Gemeenschappelijke operatie' betreft een meer decentrale organisatiestructuur waarin elke entiteit in weze autonoom handelt in de uitvoering van zijn technische verantwoordelijkheden, gezien de lage coördinatie eisen, maar waarbij entiteiten ook de verantwoordelijkheid voor bepaalde controle mechanismen delen, terwijl geen van de entiteiten een leidende autoriteit bezit. 'Incidentele coördinatie', ten slotte, is een sterk decentrale organisatiestructuur waarin entiteiten alleen coördineren indien nodig en waarbij bilaterale interactie tussen de relevante entiteiten veelal voldoende is.

betekent het vervangen van energiesystemen gebaseerd op fossiele brandstoffen door energiesystemen gebaseerd op hernieuwbare energiebronnen- en dragers een verandering van gebruikte technologieën die mogelijkerwijs ook nieuw management / organisatiestructuren benodigen. De vraag wordt dan welke organisatiestructuren nodig zijn om een voldoende mate aan coherentie te herstellen voor het behoud van betrouwbaarheid. Alvorens deze vraag te beantwoorden is een blik geworpen op wat men redelijkerwijs mag verwachten op basis van voorgaande energietransities. De literatuur over energietransities en de technische en organisatorische ontwikkeling van infrastructuren laat zien dat energie infrastructuren zich zowel technisch als organisatorisch hebben ontwikkeld vanuit een decentrale, horizontale structuur tot een centrale en verticaal geïntegreerde structuur tussen 1850 en 1970 en zich sindsdien weer meer richting een decentrale technische en organisatorische operatie hebben begeven. Hierdoor lijkt men te kunnen stellen dat centrale en decentrale netwerken schijnbaar overeenkomen met min of meer verticaal geïntegreerde vormen van organisatie tussen entiteiten. Daarnaast blijkt echter dat technische en organisatorische ontwikkelingen in energie infrastructuren weliswaar invloed op elkaar hebben, maar dat beide dimensies toch vooral hun 'eigen gang' gaan, dat wil zeggen gedreven worden door eigen, onafhankelijke drijfveren.

Het overbruggen van de techno-organisatorische scheiding

Het tweede deel behandelt de belangrijkste uitdaging van dit onderzoek: hoe technologische kenmerken uit te drukken in termen van hun organisatorische vereisten. Dit gebeurt in twee delen: eerst door het ontwikkelen van een raamwerk dat stapsgewijs de overstap van de technische kenmerken van energie infrastructuren naar de bijbehorende organisatiestructuren mogelijk maakt; daarna door het verkennen van dit raamwerk op de belangrijkste hedendaagse energiedragers in Nederland (benzine, aardgas en elektriciteit) en de feedback te gebruiken voor het verfijnen van het raamwerk. Het resulterende raamwerk kent de volgende vier stappen.

Stap één identificeert vier zogenaamde kritische technische functies, i.e. interoperabiliteit, interconnectiviteit, capaciteitsbeheer en systeembeheer[182], en diens

[182] Interoperabiliteit richt zich op de wederzijdse interacties tussen netwerk onderdelen (Finger et al. 2006, 11-12) zoals de complementariteit tussen energiebronnen en leveringssystemen (spanningsniveaus en elektriciteitsdraden) of energie-eigenschappen en applicatie eisen (de kwaliteit van aardgas en huishoudelijke ketels). Interconnectiviteit betreft de fysieke verbindingen van de verschillende netwerken die gelijksoortige of aanvullende taken uitvoeren (Finger et al. 2006, 11-12). Dit omvat het faciliteren van de verbinding tussen de lokale distributienetten en nationale transmissienetwerken en de planning van netwerkextensies. Capaciteitsbeheer heeft betrekking op de toewijzing van schaarse netwerkcapaciteit aan bepaalde gebruikers of toepassingen (Finger et al. 2006, 11-12). Problemen hebben betrekking op het opereren en balanceren van het netwerk, capaciteitsallocatie, de onderhoudsplanning en de lange-termijn planning van netwerk- en productiecapaciteit (Künneke en Finger 2007, 310-311). Tot slot, systeembeheer heeft betrekking op de vraag hoe het gehele systeem wordt beheerd en hoe de kwaliteit van de dienstverlening wordt gewaarborgd (Finger et al. 2006, 11-12). Dit betekent meestal het afstemmen van productie en verbruik (zowel kwantitatief als

controlemechanismen die energie infrastructuur entiteiten voor het verzorgen van betrouwbare operatie in de gaten dienen te houden. De focus op deze technische functies komt voort uit het feit dat zij juist die aspecten van technische operatie vertegenwoordigen die invloed hebben op de coördinatie tussen de entiteiten van infrastructuren in plaats van slechts de werking van de technische artefacten zelf (die over het algemeen een entiteit interne zorg zijn). Zodoende openen de vier technische functies de weg van technologie naar organisatie. Daarnaast helpen ze ook ons te concentreren op de belangrijkste operationele taken van entiteiten in een energie infrastructuur in plaats van de grote hoeveelheid aan betrokken technologieën.

Nadat de technische functies van een energie infrastructuur in kaart zijn gebracht, worden vervolgens in stappen twee en drie de twee belangrijkste aspecten van organisatiestructuren geïdentificeerd: de verantwoordelijkheden van de betrokken entiteiten bij de organisatie van elk van de functies (wie doet wat, wanneer, en hoe) en de aard van hun interactie (waarbij de coördinatie op een hiërarchische-horizontale schaal wordt ingedeeld). Voor de verdeling van verantwoordelijkheden is gebruik gemaakt van de entiteiten van de technische keten: bronnen, opwekking, groothandel, transport, opslag, distributie, meting, detailhandel, consumenten, en toezichthouders. Daarnaast is de mate van betrokkenheid geclassificeerd van geen tot leidende in zes gradaties.[183] De verantwoordelijkheden van de huidige en vroegere (vóór de liberalisering) entiteiten in de werking van elektriciteit, aardgas en benzine systemen bieden daarbij een praktisch referentiepunt aan de hand waarvan de functies van een toekomstige waterstof infrastructuur aan entiteiten toe te wijzen zijn. Voor de beoordeling van de aard van interactie wordt gekeken naar de coördinatie eisen van de kritische technische functies. Hiervoor is allereerst een interessant voorstel van Künneke et al. (2008) onderzocht. In hun artikel worden transactie eigenschappen vanuit de transactiekosten theorie gerelateerd aan de controlemechanismen die nodig zijn om kritische technische functies te faciliteren. Aangezien deze eigenschappen ook kunnen worden gekoppeld aan de mate van centrale coördinatie nodig om hen te faciliteren, is het mogelijk een brug te slaan tussen de twee dimensies van socio-technische systemen. Daarnaast is de literatuur over ongevallen in grote socio-technische systemen geraadpleegd. Deze wijst op een aantal infrastructurele en situationele kenmerken die de noodzaak en de werking van de controlemechanismen en dus ook de coördinatie eisen kunnen beïnvloeden: de complexiteit van het netwerk, de intensiteit van het netwerkverkeer, de onderlinge afhankelijkheid van netwerk delen, de flexibiliteit van de entiteiten, de dynamische omgeving waarin de operatie plaatsvindt en de aanwezigheid of afwezigheid van routines en dominante ontwerpen.

kwalitatief) en het zorgen dat het energiesysteem in staat is zich aan te passen aan veranderende omstandigheden.

[183] De zes gradaties zijn: geen betrokkenheid, indirecte betrokkenheid (het handelen van entiteiten beïnvloedt slechts rakelings en zonder intentie de operatie of planning), ondersteunende betrokkenheid (het zetten van richtlijnen, voorzien van gegevens, toezicht houden), zwakke directe betrokkenheid in de dagelijkse operatie (entiteiten zijn formeel betrokken bij operaties), sterke directe betrokkenheid (betrokkenheid bij belangrijke operationele verantwoordelijkheden) en leidinggevende betrokkenheid (als een entiteit de centrale coördinatie als taak heeft (systeembeheerder).

Uiteindelijk worden zes graden van centrale coördinatie onderscheiden gaande van autonome entiteiten die zonder behoefte aan coördinatie kunnen opereren tot de noodzaak van een centraal coördinerend centrum dat dicteert en begeleidt.[184]

Ten slotte worden de resultaten van stap twee en drie samengebracht om tot een overkoepelende organisatiestructuur te komen. Hiertoe wordt eerst per technische functie de betrokkenheid van de entiteiten bij het faciliteren gecombineerd met de coördinatie eisen tussen de entiteiten om zo de vereiste organisatiestructuur van de technische functie vast te stellen. Daarna worden de resulterende organisatiestructuren van alle vier technische functies met elkaar gecombineerd om tot de overkoepelende organisatiestructuur voor alle functies te komen. Ten aanzien van het eerste moet men zich de vraag stellen welke combinatie leidt tot welke organisatiestructuur. Om de immense complexiteit van alle mogelijke combinaties te vermijden, is een en ander vereenvoudigd. De verdeling van verantwoordelijkheden is in twee categorieën opgesplitst: bestaat er een entiteit die veel meer betrokken is dan anderen of zijn juist meerdere entiteiten ongeveer gelijk betrokken bij het faciliteren van een technische functie? De coördinatie eisen van technische functies zijn opgesplitst in zijnde of sterk of zwak (centrale en decentrale coördinatie). Hierdoor is het mogelijk de combinaties van resultaten van stappen twee en drie te relateren aan de vier ideaaltypen van organisatiestructuren (verticale integratie, leidende entiteit, gemeenschappelijke operatie, en incidentele coördinatie). Ten aanzien van het combineren van de benodigde organisatiestructuren van de vier functies zijn de gedetailleerde resultaten van stappen twee en drie per technische functie geherinterpreteerd in termen van infrastructuurwijde organisatorische vereisten. Hiervoor zijn allereerst grafisch alle aansluitingen vertegenwoordigd in een overzicht van de keten, terwijl de volgende logica voor het komen tot een overkoepelende organisatiestructuur als leidraad is genomen: die entiteiten belast met de kritische technische functies die centrale coördinatie vereisen, dienen als de voornaamste entiteiten in de organisatie van de totale infrastructuur te worden gezien en die entiteiten die betrekking hebben op minder kritische technische functies kunnen verticaal geïntegreerd zijn, gescheiden zijn, of zelfs geheel autonoom opereren, afhankelijk van de vereiste mate van centrale coördinatie. Met andere woorden, we kijken eigenlijk naar de belangrijkste entiteiten en functies die betrokken zijn (eenheden met veel verantwoordelijkheden en taken die behoefte hebben aan centrale coördinatie) en zetten vanuit dat perspectief het geheel in elkaar.

Op basis van deze overwegingen is een raamwerk voor afstemming voorgesteld (en geoperationaliseerd) langs vier opeenvolgende stappen:

Figuur 1. Een raamwerk voor afstemming

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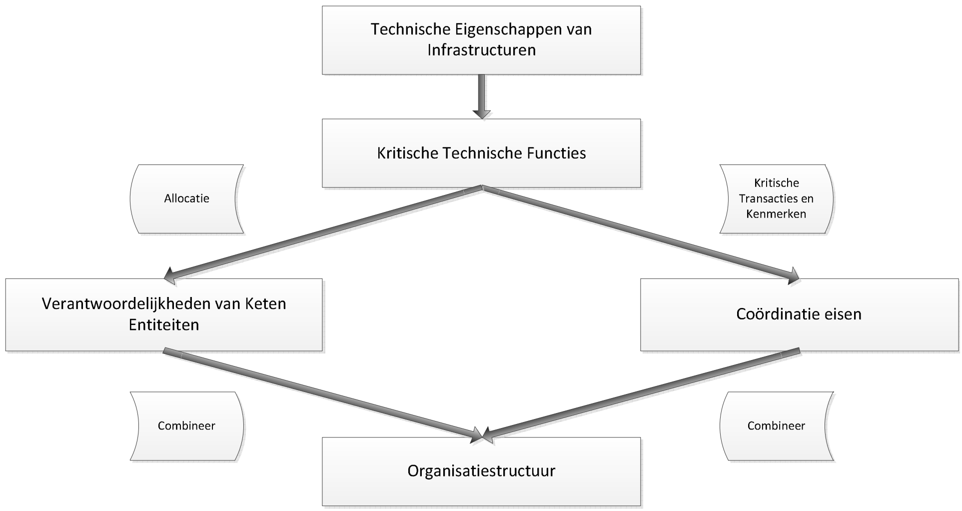
[184] De zes gradaties zijn: niet critical (autonome entiteiten handelen zonder noodzaak van coördinatie), lage criticality (autonome entiteiten die vrijwillig hun opereren aanpassen aan een gemeenschappelijke norm of doel), medium criticality (gemeenschappelijke operatie gebaseerd op afspraken tussen autonome entiteiten), hoge criticality (doorgaande coördinatie tussen de belangrijkste entiteiten), zeer hoge criticality (centrale coördinatie vanuit een centrum dat monitored en ingrijpt wanneer nodig) en meest critical (centrale coördinatie vanuit een centrum dat dicteert en begeleidt.



De casus van een transitie naar waterstof

Na het opstellen van het raamwerk voor afstemming kan het worden toegepast op de casus van een overgang naar het gebruik van waterstof als motor brandstof in Nederland. Deze toepassing dient om het gebruik van het raamwerk te illustreren, haar concepten te concretiseren door ze toe te passen, verdere verfijning te stimuleren en het nut van het raamwerk voor praktische doeleinden te verhelderen. De overgang naar het gebruik van waterstof als motorbrandstof zoals ontwikkeld door het Energieonderzoek Centrum Nederland (ECN) voor het HyWays project van de Europese Unie (EU), geeft een interessante en uitdagende casus om het raamwerk op te exploreren omdat het een grote verscheidenheid van waterstof technologieën en netwerken tussen 2010 en 2050 voorziet. Zie Tabel 1 voor een overzicht van beschikbare waterstoftechnologieën voorzien in de HyWays routekaart. Hieronder zijn zowel de casus als de toepassing van het raamwerk kort samengevat.

Tabel 1. HyWays waterstofketens voor Nederland

Keten	Bron	Productie	Eerste Conversie	Transport en distributie	Tweede Conversie	Eind-gebruik
1	aardgas	onsite SMR	-	-	CGH2	mobiel & stat.
2	aardgas	centrale SMR	-	pijpleiding	CGH2	mobile & stat.
3	aardgas	centrale SMR	liquefactie	LH2 wagen	LH2	mobiel
4	(harde) kolen	gasificatie + CCS	-	pijpleiding	CGH2	mobiel & stat.
5	biomassa	gasificatie	-	pijpleiding	CGH2	mobiel & stat.
6	offshore wind	centrale electrolyse	-	pijpleiding	CGH2	mobiel & stat.

Bron: Mulder 2005, slide 6 en EU HyWays Member State report 2007, 54.
Legenda: LH2 staat voor vloeibare waterstof; CGH2 staat voor gecompresseerd waterstofgas; stat. staat voor stationair; SMR staat voor steam methane reforming; CCS staat voor CO2 afvang en opslag.
NB: Mulder wijkt af van het HyWays rapport door stationaire toepassingen te vermelden.

Volgens de HyWays routekaart[185] wordt waterstof rond 2020 beschikbaar verwacht in drie gebruikerscentra: Rotterdam, Amsterdam en Arnhem-Nijmegen. Waterstof wordt opgewekt uit aardgas door kleinschalige onsite reforming op of nabij de tankstations en geleverd door tankwagens (na het vloeibaar maken) aan stedelijke tankstations verder verwijderd van aardgas pijpleidingen of tankstations langs de belangrijkste snelwegen die de centra verbinden. In Rotterdam wordt ook industriële waterstof gebruikt om lokale tankstations te vullen. De vroege gebruikerscentra zijn in termen van netwerkoperatie eenvoudig van opzet en zelfstandig, dat wil zeggen er ontbreekt een infrastructurele verbinding tussen de gebruikerscentra, maar waterstofvoertuigen moeten in staat zijn om in ieder van hen te tanken. Op de middellange termijn (2035) zullen zich naar verwachting grote veranderingen voordoen als het gevolg van een snel stijgende vraag en aanbod van waterstof. Men verwacht dat zich vanuit Rotterdam een regionaal waterstof pijpleidingennetwerk zal ontwikkelen dat uiteindelijk de Randstad voorziet, terwijl het Arnhem-Nijmegen gebruikerscentrum ten opzichte hiervan onafhankelijk blijft. In termen van productie wordt verwacht dat grootschalige centrale faciliteiten onsite productie zullen vervangen, terwijl kolen en biomassa zich aanbieden als potentiële bronnen naast aardgas. De proliferatie van waterstof pijpleidingen in en tussen steden en de noodzaak van grootschalige productie van waterstof om aan de stijgende vraag te voldoen, verandert de rol van onsite productie en waterstof levering per vrachtwagen. Enerzijds dreigt onsite

[185] De data van HyWays zijn licht aangepast. Deze waren oorspronkelijk 2010, 2030 en 2050. Dit komt met name omdat latere werken van ECN rondom de invoering van waterstof als motor brandstof de tijdstippen hebben aangepast. Echter, de stappen zelf zijn onveranderd gebleven.

productie alleen interessant te blijven in afgelegen, meer landelijke gebieden. Anderzijds kunnen waterstof tankwagens het bereik van onsite faciliteiten op het platteland vergroten, dienen als een extensie van het pijpleidingennetwerk en fungeren als noodvermogen in het geval van vraag en aanbod fluctuaties in door pijpleidingen voorziene gebieden. Dat is waarschijnlijk hard nodig om de snel groeiende infrastructuur tegemoet te komen en betrouwbare levering te garanderen. Op de lange termijn (2050) is naar verwachting een nationaal netwerk van pijpleidingen geïnstalleerd dat de meeste Nederlandse steden in het westen, zuiden en oosten met elkaar verbindt. Alleen in het noorden zullen waarschijnlijk nog een aantal onsite productiefaciliteiten en waterstof tankwagens concurreren en/of noodzakelijk zijn om dekking te garanderen. Dit nationale netwerk van pijpleidingen begint nu echter wel complexer te worden door de mogelijkheden die de interconnectiviteit biedt voor waterstofproducenten om meerdere markten te bereiken en het toenemende aantal tankstations. Bovendien wordt het netwerk meer en meer gevoed door hernieuwbare waterstofbronnen terwijl het gebruik van fossiele brandstoffen in grote installaties verminderd of is onderworpen aan het afvangen en opslaan van CO2. Waterstofhandel zou wellicht een realiseerbare doelstelling kunnen zijn, temeer omdat de infrastructuur in een wat stabielere, minder turbulente fase komt.

Met het weergeven van de drie HyWays transitiestadia zijn we klaar om met behulp van het raamwerk de aanvullende organisatorische vereisten te vinden en een organisatorische routekaart naast de technische te plaatsen.

Anno 2020 is interoperabiliteit de grootste zorg. Normen en standaarden dienen te worden gezet en nageleefd en een wildgroei ervan te worden voorkomen. Systeembeheer en interconnectie zijn een kleinere kwestie; enerzijds dient de vraag naar waterstof gestimuleerd te worden in gebieden verder verwijderd van onsite productie wil waterstof als markt groeien, anderzijds dienen tankwagen bedrijven hun netwerk met die van onsite producenten te coördineren. Capaciteitsbeheer is verwaarloosbaar gezien de focus op onsite productie en truckdistributie van waterstof. Wat betreft de verantwoordelijkheden van entiteiten zien we dat onsite producenten een centrale positie innemen, terwijl tankwagen bedrijven, tank stations, en de regulator ongeveer gelijk betrokken zijn, zij het voor verschillende functies (planning vs. dagelijkse uitvoering). Daar komt bij dat onsite producenten en tankstations vaak dezelfde entiteit zijn, terwijl vrachtwagenbedrijven zowel zelfstandig zouden kunnen opereren als geïntegreerd zouden kunnen worden bij producenten. Vandaar dat de operationele verantwoordelijkheden binnen de gebruikerscentra zowel bij een enkele entiteit (de onsite producent) kan liggen als verspreid kan zijn over de entiteiten die betrokken zijn binnen ieder gebruikerscentrum. In termen van coördinatie vereist interoperabiliteit en in mindere mate interconnectiviteit en systeembeheer enige consultatie. Dit betreft voornamelijk het vaststellen van normen door middel van overleg tussen belanghebbenden op de lange termijn en hun naleving door entiteiten plus overheidstoezicht op de korte termijn. Daarnaast was het noodzakelijk te coördineren voor de opbouw van de netwerkverbinding tussen de centra op de lange termijn. Aandacht voor het coördineren van de groei van vraag en aanbod is ook wenselijk. Wat betreft de dagelijkse operatie, de combinatie van lage coördinatie eisen en gefragmenteerde operationele verantwoordelijkheden vanuit een nationaal perspectief leidt tot een organisatiestructuur van incidentele coördinatie. Echter, met het oog op de toekomstige integratie van de drie gebruikerscentra en het zorgen dat er geen divergente standaarden ontwikkeld worden, dienen de betrokken entiteiten elkaar regelmatig te consulteren over de te volgen routekaart.

In 2035 worden systeembeheer en interconnectie de belangrijkste functies. Dit komt met name doordat in deze dynamische fase de vraag naar waterstof en de productie van waterstof in rap tempo toenemen en het netwerk grote veranderingen ondergaat om aan deze groei tegemoet te komen. Zo verandert het netwerk van onsite productie en vrachtwagens naar centrale productie en pijpleidingen. Daarnaast worden ook nog de gebruikerscentra deels gekoppeld. Capaciteitsbeheer begint ook een kwestie te worden voor het pijpleidingensysteem, zij het op regionaal niveau en ondersteund door opslagmogelijkheden en truck distributie. Interoperabiliteit wordt echter minder nu de basistechnologieën lijken te zijn bepaald en afwijken daarvan kostbaar is voor entiteiten. De verantwoordelijkheden zijn anno 2035 sterk verdeeld over een groot aantal betrokken entiteiten. Enerzijds zijn centrale producenten, de pijpleidingbeheerder, truck distributeurs en tankstations (retail en meting) sterk betrokken bij de technische werking in het westen van Nederland, terwijl onsite producenten, truck distributeurs en tankstations dominante actoren blijven in het Arnhem-Nijmegen gebruikerscentrum en in de meer landelijke gebieden. Echter, de pijpleiding beheerder speelt wel de centrale rol in de Randstad. In deze momentopname zijn de meest strikte coördinatievereisten noodzakelijk voor issues van interconnectiviteit en systeembeheer, terwijl capaciteitsbeheer een sterk opkomende functie is. Centrale coördinatie van pijpleiding activiteiten wordt noodzakelijk geacht voor het functioneren van het systeem in deze dynamische omgeving. Hoe anders is de snelle stijging van de vraag, aanbod en netwerk te coördineren? Tegelijkertijd spelen trucks echter een cruciale rol in het flexibel houden van de algehele infrastructuur. Kwesties m.b.t. interoperabiliteit daarentegen benodigen minder coördinatie. Deze combinatie van strikte coördinatie eisen en gefragmenteerde operationele verantwoordelijkheden noodzaakt volgens het raamwerk een organisatiestructuur van verticale integratie (om de frequente interactie en benodigde coördinatie tussen de entiteiten rondom het pijpleidingnetwerk te stroomlijnen) ondanks dat trucks de nodige flexibiliteit bieden voor de stabiele opbouw van de infrastructuur in de dynamische setting.

Rond 2050 wordt capaciteitsbeheer de belangrijkste technische functie aangezien het pijpleidingnetwerk vrijwel het gehele land voorziet en het houden van diens balans van nationaal belang wordt. Nu het netwerk gebouwd is, zijn de zorgen over interconnectiviteit en systeembeheer aanzienlijk minder gezien men zich met het beheer van bestaande aansluitingen kan bezighouden zonder de beslommeringen van fundamentele toekomstige uitbreidingen en consumptie en aanbod patronen het matchen van vraag en aanbod vergemakkelijken. Interoperabiliteit valt vrijwel weg als kwestie nu het pijpleidingensysteem het dominante design is geworden en andere technologieën / entiteiten zich hieraan zullen moeten aanpassen wil men van het netwerk gebruik maken. Het verschuiven van de focus op de werking van het netwerk in plaats van de bouw van de infrastructuur kenmerkt de verantwoordelijkheden en coördinatie vereisten van deze fase. Ten aanzien van de verantwoordelijkheden blijkt dat terwijl er nog steeds veel entiteiten betrokken zijn, de pijpleidingbeheerder het centrum van operatie wordt met vrachtwagen distributeurs, onsite en centrale producenten, handelaren, tankstations, en de toezichthouder in een ondergeschikte rol. Met betrekking tot coördinatie vereisten, benodigen kwesties met betrekking tot het beheer van de netwerkcapaciteit de meest centrale controle voor het waarborgen van systeemcomplementariteit terwijl tegelijkertijd de coördinatie eisen voor interconnectiviteit hoog blijven. De eisen van systeembeheer en interoperabiliteit nemen daarentegen af. Met andere woorden, de algehele coördinatie eisen blijven streng, maar verschuiven naar een focus op het netwerk. De combinatie van strikte, centrale coördinatievereisten en de pijpleidingbeheerder als centrale verantwoordelijke leidt tot een organisatiestructuur van een leidende entiteit.

De tabel hieronder vat beknopt de techno-organisatorische routekaart samen. Daarbij vormt de huidige situatie omtrent de distributie van benzine het startpunt.

Tabel 2. Een techno-organisatorische routekaart

Fasen	2010	2020	2035	2050
Technische routekaart	Nationaal benzine netwerk gebaseerd op truck distributie	Onafhankelijke lokale centra gebaseerd op on-site waterstof ondersteund door trucks	Opkomend nationaal waterstof pijpleiding netwerk ondersteund door truck distributie	Nationaal waterstof pijpleiding netwerk (trucks alleen ruraal)
Betrokkenheid entiteiten	Meerdere entiteiten ongeveer gelijk betrokken Taken scheidbaar	Twee voornaamste entiteiten Taken scheidbaar	Meerdere entiteiten ongeveer gelijk betrokken Pijpleiding taken onafscheidbaar	Kern netwerk entiteit Pijpleiding taken onafscheidbaar
Coördinatie eisen	Soepele coördinatie eisen Bestaande operationele routines Geen regelmatige coördinatie voor planning en taken	Soepele coördinatie eisen Focus op complementariteit componenten Regelmatige coördinatie voor planning, niet voor taken	Strikte coördinatie eisen Coördinatie om veranderende omstandigheden te meesteren; trucks en opslag voor nodige flexibiliteit.	Strikte coördinatie eisen Complexiteit in plaats van dynamiek Centralisatie van controle taken in pijpleidingbeheerder
Organisatie-structuur	Incidentele coördinatie	Gemeenschappelijke operatie / Incidentele coördinatie	Verticale integratie	Leidende entiteit

De tabel dient niet alleen als een handige samenvatting van de routekaart, maar wijst ook op een aantal ontwikkelingen die laten zien hoe technische kenmerken kunnen veranderen tijdens het ontstaan of de opbouw van een netwerk en hoe de organisatie van een infrastructuur zou moeten veranderen in reactie daarop om betrouwbaar functioneren te garanderen in elk van de fasen. Als we de resultaten generaliseren, suggereert de tabel een beweging in de vier kritische factoren van interoperabiliteit naar interconnectiviteit en systeembeheer naar uiteindelijk capaciteitsbeheer. In termen van betrokkenheid van entiteiten, zien we dat in de vroege stadia onsite producenten en tankwagen bedrijven een dominante rol spelen terwijl later centrale producenten en pijpleidingbeheerders een meer prominente rol krijgen. Retailers behouden hetzelfde niveau gedurende de transitie. De coördinatie eisen ten slotte nemen over het algemeen toe gedurende de voortgang van de transitie alhoewel de overstap van 2035 naar 2050 eerder een andere aard van centrale coördinatie betreft dan een toename ervan. Over het algemeen kan men stellen dat de aandacht met betrekking tot betrouwbaarheid zich lijkt te verplaatsen van het operationeel krijgen van infrastructuur technologieën naar het garanderen van het complementair opereren en beheren van het gebruik van het netwerk. Zo zien we ook dat de organisatiestructuur verschuift van een waarbij meerdere autonome entiteiten incidenteel coördineert en gemeenschappelijk opereert naar een die gebaseerd is op verticaal geïntegreerde structuren waarbij de focus zich uiteindelijk richt op de centrale rol van de netbeheerder.

Ervaringen en implicaties

Over het geheel genomen lijkt het raamwerk voor afstemming aan de verwachtingen te voldoen. Het raamwerk slaagt er in de belangrijkste operationele aspecten van toekomstige hernieuwbare energiesystemen aan de hand van een paar simpele concepten te bespreken (de kritische technische functies), zorgt voor een methodisch onderzoek naar de betrokkenheid van entiteiten (aan de hand van de infrastructuur componenten) en hun coördinatie eisen (uitgedrukt in termen van verticale integratie), en maakt de vaststelling van de algehele organisatiestructuur op een ordelijke wijze mogelijk. Zodoende lijkt het raamwerk de benodigde instrumenten of richtlijnen te presenteren om complexe toekomstige hernieuwbare energiesystemen te ontleden en een goed uitgangspunt te bieden voor de verdere exploratie van de relatie tussen de technische en sociale dimensie van energie infrastructuren in het licht van betrouwbaarheid.

Toch zijn er enkele punten voor verbetering. Ten eerste zou de eerste stap meer ruimte moeten bieden aan een moment van ontwikkeling tussen het plannen en faciliteren van technische functies. Zo komen dynamische aspecten beter tot hun recht. Daarnaast lijkt het raamwerk te zijn afgestemd op een meer mechanische werking van infrastructuren; het valt nog te bezien hoe het om kan gaan met zaken als informatiebeheer zoals bijvoorbeeld smart grids lijken te vereisen. Moet het worden behandeld als een vijfde technische functie of is ICT beter begrepen als een technologisch kenmerk van energie infrastructuren dat vorm geeft aan de keten en de werking ervan onderligt? Wat betreft de tweede stap, dient men voorzichtig te zijn met vergelijkingen tussen bestaande en toekomstige infrastructuren. Het blijft bijvoorbeeld enigszins twijfelachtig in hoeverre de decentrale netwerken van de 19e eeuw als voorbeeld kunnen dienen voor het decentrale karakter van sommige toekomstige duurzame energiesystemen. De derde stap was het meest problematisch. Twee veel voorkomende uitdagingen zijn de moeizame inschatting en classificatie van de coördinatie eisen van controle mechanismen en de centrale rol die capaciteitsbeheer inneemt in het bepalen van de algemene coördinatie eis. De voornaamste kwestie was echter hoe het effect van de verschillende infrastructurele en situationele kenmerken op de coördinatie eisen van controle mechanismen te wegen. Hier is simpelweg geen harde maatstaf voor. De laatste stap ten slotte benodigd een vereenvoudiging van de verscheidenheid van mogelijke organisatiestructuren in vier ideaaltypen. Hoewel dit de discussie van mogelijke uitkomsten stroomlijnt en bespreekbaar houdt, blijft natuurlijk de vraag of deze vier in staat zijn om een overzicht te geven van de verantwoordelijkheden en coördinatie eisen van de entiteiten. Een ander probleem is het combineren van de organisatiestructuren van de vier technische functies in één algemene structuur. De problemen van de integratie van uiteenlopende netwerken als onsite productie, vrachtwagens en pijpleidingen in de 2035 waterstof momentopname zijn hier een voorbeeld van. Tot slot is er de mogelijkheid verder te gaan dan de organisatiestructuur; welke ondersteunende institutionele arrangementen zijn nodig?

De mogelijkheid om de vereiste organisatiestructuren voor het betrouwbaar opereren van toekomstige hernieuwbare energie infrastructuren te vinden, biedt ook de mogelijkheid een organisatorische routekaart aan de technisch-economische toe te voegen. Dit heeft een aantal interessante implicaties. Ten eerste kunnen we zien dat voor de betrouwbare werking van hernieuwbare energiesystemen de organisatorische vereisten variëren in verschillende stadia van ontwikkeling. De vraag is of aan deze veranderingen in de organisatie kan worden voldaan. Het introduceren van nieuwe technologieën zou aanzienlijk gemakkelijker kunnen blijken dan het veranderen van de organisatiestructuur. De langdurige en lastige liberalisering en privatisering zijn hier een voorbeeld van. Ten tweede, in hoeverre zijn de technisch-economische en organisatorische logica conflicterend? De HyWays roadmap was gebaseerd op een wenselijke technisch-economische voortgang, maar hebben nu andere waterstof opties of ontwikkelingspaden de voorkeur gezien de organisatorische vereisten? De begrippen organisatie lock-in en pad-afhankelijkheid zouden derhalve moeten worden opgenomen in de planning van routekaarten voor toekomstige duurzame energiesystemen. Ten derde, omdat het raamwerk helpt bij het opzetten van een organisatorische routekaart, kan het worden gebruikt als een instrument door beleidsmakers om de organisatorische vereisten en de bredere implicaties van technische veranderingen in energie infrastructuren te beoordelen en een beleid uit te stippelen voor de gezamenlijke ontwikkeling van technische en organisatorische aspecten. Daarnaast kunnen de infrastructuur entiteiten reflecteren op hun veranderende rol en verantwoordelijkheden met betrekking tot betrouwbaarheid. Dit helpt hen ook bij investeringsbeslissingen.

Curriculum Vitae

Daniel Scholten was born in St. Johann in Tirol, Austria, on the 26th of April 1981. He graduated from the Gelders College in Arnhem 1999, receiving a gift from the German Ambassador for his outstanding achievements in the German language. He then received the degree of Master of Science in Political Science at the Radboud University in Nijmegen in 2003 and obtained with distinction an Executive Master's Degree in International and European Relations & Management at the Amsterdam School of International Relations of the University of Amsterdam in 2006. Afterwards he was employed as a ski instructor in Fieberbrunn, Austria (2003-2004), and as a statistical researcher at Statistics Netherlands in The Hague (2006-2007).

In August 2007 he started as a PhD student at the Economics of Infrastructures section of the Faculty of Technology, Policy and Management of the Delft University of Technology, where he worked on identifying the organizational requirements for the reliable operation of future renewable energy systems. Next to his PhD research, he has been assistant editor of the international journal Competition and Regulation in Network Industries since October 2007, becoming the managing editor in November 2011. In addition, he has been an affiliated research fellow of the Energy Programme Asia of the International Institute for Asian Studies in Leiden since 2006, where he investigates transitions to sustainable energy systems in an international perspective, and has been faculty at the Department of International Relations of the Webster University Leiden since 2008, where he teaches International Political Economy.

As of November 2011 he is assistant professor at the section Economics of Infrastructures of the Faculty of Technology, Policy and Management of the Delft University of Technology. He specializes in the institutional requirements and (geo)political implications of future renewable energy systems, mostly solar and wind based. He is currently involved in a number of research projects, the organization of conferences and workshops, and book projects in this regard.