

EDGaR D1

Integrating local & regional energy systems for enhancing sustainability

Work Package 3

Designing Institutions for Future Energy Systems

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Abstract

The integration of renewable energy into the Dutch energy infrastructure raises interrelated operational and market challenges. In their efforts to address them, engineers and economists approach the design of electricity infrastructures very differently, however. While economists focus on a market design that addresses potential market failures and imperfections, opportunistic behaviour, and social objectives, engineers pay attention to infrastructure assets, a robust network topology, and control system design to handle flows and eventualities. These two logics may be complementary, but may also be at odds. Moreover, it is generally unclear what design choices in one dimension imply for the other. A new and more comprehensive design framework is necessary that bridges the engineering and economic perspectives on energy infrastructure design.

This work package develops a comprehensive institutional design (CID) framework for the integration of renewable energy technologies into energy electricity systems and markets. To this end, it elaborates the different design perspectives of engineers and economists regarding energy infrastructures, highlighting the importance of aligning both perspectives, and proposes a framework for a more comprehensive institutional design of complex adaptive socio-technical systems. The resulting framework focuses on aligning the form of infrastructure access of actors, division of responsibilities among actors, and type of coordination between actors in system and market design efforts, given a certain systemic and institutional environment.

The research's main contribution lies in the development of a framework that combines *and* aligns engineering and economic design possibilities whilst establishing the institutional arrangements for (future) energy systems and markets. This work package hence presents a tool for interested parties to work with; application to cases is left for follow-up research. Once applied to specific cases, practical beneficiaries of the research are policy makers (insights into the institutional arrangements required to optimize performance) and industry (overview of changes in operational responsibilities and business models). It also aids in overseeing the broader institutional implications of technical developments (and vice versa) and stimulates awareness of lock-ins and path-dependencies in this regard.

Keywords

Energy infrastructures, renewable energy, system design, market design, comprehensive institutional design.

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1. Introduction - Rationale for the EDGaR D1 Study

Increasing fossil fuel scarcity and deteriorating environmental conditions call for a transition towards a more sustainable energy system. In response, the Netherlands has committed itself to a challenging target for 2050: energy related CO₂-emissions should be reduced by 80% as compared to the 1990 level (European Commission, 2011, Energy Roadmap 2050, Brussels). To achieve this low-carbon future, a multitude of renewable energy technologies and energy efficiency measures exist. The EDGaR D1 research project focuses on one specific possibility in this light: it aims to contribute to the development of an efficient and effective low-carbon energy system in the Netherlands by a further integration of the electricity, natural gas and heat energy infrastructures at the local and regional level (close to the end user), both from a technical and socio-economic perspective. The notion of integration should be broadly interpreted; it also includes the system integration of renewable energy generation, energy efficiency, and storage technologies. Special emphasis goes to distribution companies, their roles and responsibilities in operating different integrated energy system configuration, in facilitating local energy markets, and ensuring public service obligations.

The point of departure for the research project is that the integration of electricity, natural gas, and heat energy systems poses fundamental new challenges in the design, operation, and regulation of future power systems. From a technical perspective, special attention should go to those technical functions that are fundamental in the operation of future integrated energy systems:

- Which technologies should we adopt (wind, solar pv, biomass, ccs)? Where to locate low or zero-carbon energy production facilities? What scale of distributed production can we expect where?
- How to deal with the intermittent nature of production from renewable sources? How to increase system flexibility to facilitate large upswings and downswings in the energy production from intermittent sources (“start-stop”)? What about back-up production capacity in case the production capacity is low and the system load is high (“high load”) or energy buffering in case of high production and low system load (“low load”)? Should we aim for large centralised solutions (building cross-border interconnections and overlay networks across Europe, invest in large-scale energy storage) or for small decentralised solutions (increase demand response via implementation of smart grid applications)? Short-term balancing?
- What steps regarding energy storage and conversion are necessary to run integrated energy systems? At which steps during operation should conversions occur?
- How to reinforce the transmission and distribution networks so that they may facilitate intermittent production from centralized and distributed production sites?
- How to coordinate technology and production choices with infrastructure development? Should we utilize existing infrastructures to the maximum or build completely new network capacity?

The successful integration of the electricity, natural gas, and heat energy systems at the local and regional level in the Netherlands is also strongly related to the institutional conditions that govern these sectors. Some important issues in this respect are:

- How to harmonize the technical, economic, and regulatory specificities of these traditionally distinct sectors? How may the ongoing process of liberalization affect integration efforts; does it help them to converge laws and regulations in gas, electricity and heat?
- Considering the local and regional focus of the research: will the distribution companies obtain the responsibility to prioritize the transport of energy from sustainable sources (which could be done by network balancing in the gas grid as well as in the electricity grid).
- How to deal with new or changing market structures? Consider in this respect, for example, the impact of the possible emergence of many small-scale prosumers and energy storage companies that will challenge the market position of traditional gas-, electricity- and heat companies. Moreover, new trading relationships may evolve such as united consumers, united producers, or neighbor-to-neighbor trading. Metering, pricing and tariffing are important aspects in this respect, but also the possibly changing need for unbundling of the network related activities from storage, production and trade.
- How will local flex/spot markets interact with the regional system, which consequences could this have for the willingness to invest in local/regional flexibility measures in the electricity and gas grids in large scale renewable projects such wind parks?
- Which contractual models at the regional / local level could contribute to an increased sustainability, conditional to affordability and security of supply? How should balancing requirements be set and be treated contractually? How could “optimality” of integrated e-g-h grids be defined from the various actors’ viewpoints?

The EDGaR D1 project consists of four work packages that build upon each other to provide the tools necessary for investigating the possibilities for an efficient and effective low-carbon local and regional energy system in the Netherlands and that do justice to the complex and multidisciplinary nature of the project. The tools can then be jointly utilized by EDGaR project partners in applications on practical cases.

The first work package executed by ECN entails the development of a model (opera) for the economic assessment of the technical options for integrated local and regional energy systems in the Netherlands. Eventual output details the key feasible and desirable possibilities of various energy technologies from an economic perspective, taking into account different scenario backgrounds for the Dutch energy system, different possible technology developments, and different choices on investment in energy production and energy infrastructure assets. In doing so, ECN contributes to two research questions in particular: a) how do different technical opportunities contribute to the realization of low-carbon energy systems; b) what are the technical opportunities for integrating energy infrastructure taking into consideration the different regional and local conditions in the Netherlands? In short, WP 1 develops a model to identify those configurations of technologies that we may consider the most relevant future energy systems in the Netherlands.

The second work package executed by KIWA measures and analyzes the technical characteristics of the components for integrating the gas and electricity supply systems. It aims to determine the physical performance of the relevant local scale appliances in their interaction with each other. It takes the technical options of WP1 as a starting point but also serves as feedback to it. In addition it provides technical advice as input for WP4.

Work package 3 develops a comprehensive institutional design (CID) framework for the integration of new (renewable) energy technologies into existing energy systems and markets. The point of departure is that new energy technologies affect energy systems and markets alike but that

economists and engineers never address their responses in an interrelated fashion. As a result, a coherent framework for approaching the design of future energy infrastructures is lacking. In turn, the CID framework aims to provide the means with which to identify, interpret and address the interrelated operational and market challenges resulting from the system integration of new renewable energy technologies. The framework can be used to provide the institutional arrangements that should accompany the different possible configurations of future locally and regionally integrated E-G-H energy systems in the Netherlands (from WP1) in order to ensure that these configurations meet technical, economic, and social performance criteria. More immediate, it can serve as a guideline for framing the institutional parameters of WP4s agent-based model.

Work package 4 studies the technical/physical relationships between system components and the techno-economic relationships between actors operating these components at the hand of agent based modeling. It is carried out by TNO. The objective is to formalize these relationships in a generic, quantitative model of a coupled e-g-h distribution system, which includes the behaviors of the actors, both on the short-term (operational decision) and on the long-term (investment or contractual decisions). Input for this model comes from all other work packages. The agent based model's eventual purpose is to provide a way of 'testing' the technical, economic, and institutional recommendations (and subsequent infrastructure performance) of the previous work packages.

2. WP3: A Comprehensive Institutional Design Framework for Energy Infrastructures

2.1 Introduction

A transition to more sustainable energy system implies more than finding the optimal generation technology mix for the reduction of CO₂ emissions and diffusing them in the market. To ensure the continued technical, economic and social performance of future energy systems we also need to think about the institutional arrangements necessary to ensure the proper functioning of new technologies once they have been put in place. After all, the system integration of new (renewable) energy technologies raises numerous interrelated operational and market challenges.¹ How should the feed-in of solar PV based electricity from thousands of households be arranged? Should neighbors be allowed to exchange electricity directly on local spot markets (Bouffard and Kirschen 2008; Schleicher-Tappeser 2012)? What about the intermittency challenges, grid capacity issues, and negative energy prices that offshore wind may cause? Should we allow hour ahead markets in light of more accurate wind forecasting (EWEA 2009; Kaldellis and Kapsali 2013)? In addition, how will local energy cooperatives coexist with conventional power grids (Seyfang and Smith 2007; Walker and Devine-Wright 2008)? Adding to the challenge is that these renewable technologies do not develop in isolation; they are to be integrated simultaneously in the Dutch grid, be it at different national or local levels. Moreover, technological solutions such as smart grids or electricity storage possibilities are likely to only partly accommodate these changes (Amin and Wollenberg 2005; Akorede et al. 2010). Hence, if new renewable energy technologies are to realize their potential, the institutional arrangements of energy infrastructures need to incorporate the operational and market changes that they bring.²

The institutional design of (future) energy infrastructures is easier said than done. While plenty of insights exist in relevant literature, they are plagued by their rather fragmented nature: engineers and economists approach the matter very differently. On the one side, engineers perceive energy infrastructures as technical systems that need to function reliably and robustly. They pay attention to infrastructure assets, network topology, and control system design to handle flows and eventualities (Dutton et al. 1997).³ On the other side, economists, policy makers, and legal experts focus on market designs that address potential market failures and imperfections, opportunistic behaviour, and social objectives (Stoft 2002). They think more about energy markets that need to efficiently and effectively allocate goods and services according to societal needs.⁴ Moreover, neither of them

¹ The Dutch Energy Agreement (EZ 2013) notes offshore wind, local solar PV, energy cooperatives and smart technologies as cornerstones of a renewable energy infrastructure. These technologies challenge existing control architectures, enable new forms of electricity production, transport, and trade, and in turn require new institutional arrangements.

² At the same time, the institutions of energy markets needs to be in line with the broader institutional environment in which these systems are embedded (Williamson 2000; Spiller 2011). Countries differ greatly in the extent to which the power sector is liberalized, privatized, unbundled, and regulated. Moreover, there are country specific norms and values, often expressed in public service obligations or performance criteria that cannot be ignored (Mulder and Willems 2009).

³ Technologies are not studied as isolated physical artifacts, but as technology-as-systems (Ewertsson and Ingelstam 2005, 305). Emphasis is on deciding components and how they fit together in the delivery of a good or service, the central role of the engineer in an iterative design process that contains several fundamental steps (Hurst 2004; NASA 2008), and managing often contradictory design parameters. There is consensus that there is no 'one best way' to go about it, nor is there a generic set of design variables that engineers can turn as knobs.

⁴ Attention goes to institutions as "the rules of the game" (North 1990) that enable and constrain actor behaviour and consequently market outcomes. Typical design variables are the degree of vertical and horizontal competition and the

specifically targets energy infrastructures or large socio-technical systems in their conceptualization of design instead focusing mostly on individual technologies or standard commodity markets.

The fragmented nature is troublesome in at least three ways. First, the two design logics may be complementary, but may also be at odds. They may generate different, or even conflicting, solutions. System operation and market organization can pose conflicting requirements on actors. Energy sector liberalization, for example, opened up energy markets for a variety of actors, unbundled existing incumbents, and led to diverging economic interests among actors, while the technical operation remained that of a vertically integrated monopoly controlled from a central control room (Künneke and Finger 2007). As a result, market interests and activities of actors can start to contradict their operational roles and responsibilities. The transition towards sustainable energy integration may lead to similar divergences. Second, and more fundamentally, it is generally unclear what design choices in one dimension imply for the other. Currently we lack the means to express ex ante the implications of engineering choices on market design of energy infrastructures and vice versa. This hinders determining when we should, for example, employ a technical or market based solution to tackle a specific challenge? Third, the fragmented nature of design is especially confronting considering we have increasingly come to perceive energy infrastructures as complex adaptive socio-technical systems whose performance rests on the continuous interaction between technologies, markets, and institutions (Kroes et al. 2006; Kaijser 2005; Nelson 1994; Geels 2004; Weijnen and Bouwmans 2006; Scholten 2013; Künneke et al. 2010; Ewertsson and Ingelstam 2004; Hughes 1983). How are we to do justice to the interrelated nature of the systemic and market challenges raised by new (renewable) energy technologies?

A new and more comprehensive design framework is necessary that bridges the engineering and economic perspectives on energy infrastructure design. Only then may we adequately identify, interpret, and address (future) challenges to energy infrastructure performance.

2.2 Research Objective

There is an apparent and urgent need for an institutional design framework that allows identifying, interpreting and addressing the interrelated operational and market challenges resulting from the system integration of new renewable energy technologies. The objective of the research activities of the TU Delft is to develop such a comprehensive institutional design (CID) framework. To this end, this report elaborates the different design perspectives of economists and engineers regarding energy infrastructures, highlighting the importance of aligning both perspectives, and proposes a more comprehensive institutional design framework for energy infrastructures. This work package hence presents a tool for interested parties to work with; application to cases is left for follow-up research. The framework's immediate intended use is to provide the institutional arrangements that should accompany the different possible configurations of future locally and regionally integrated E-G-H energy systems in the Netherlands in order to ensure that these configurations meet technical, economic, and social performance criteria. Alternatively, it can also investigate the institutional requirements of new energy technologies or market dynamics that lie outside the scope of EDGaR D1, such as specific targets of the Energy Agreement regarding solar, wind, biomass, smart grid concepts, and cooperatives. In addition, it serves as a guideline for framing the institutional parameters of WP4s Agent-based Model.

process of sector reform, as influenced by its pace and scope, the gradual change of ownership and decision rights, and the types of allowed contracts or market transactions (Glachant and Finon 2000; Newbery 2005; Alexander and Harris 2005).

A word of caution: this study does not shed light on the (governance of the) transition process towards these institutional designs. It produces a snapshot of the arrangements required at a certain point in time and does not prescribe how that design comes about or develops over time.

Research Questions

- a) How do engineers and economists design energy systems and markets respectively? What concepts are available to relate both perspectives?
- b) What should a comprehensive institutional design framework of energy infrastructures focus on and how may it be applied?

2.3 Research Design

Theory

The research revolves around the development of a comprehensive institutional design framework for energy infrastructures. In light of the EDGaR D1 program it should enable us to a) identify and interpret the operational and market implications of introducing new energy technologies or system configurations into existing network architectures and b) investigate the possible institutional arrangements for ensuring operational reliability, market efficiency, and public service obligations. It builds on insights from the fields of micro-economics, industrial organization, and institutional economics as regards the design of renewable energy markets (Goodin 1998; Williamson 2000; Armstrong and Porter 2007; Joskow 2007; Perez-Arriaga 2013). It relies upon insights from the literature on socio-technical systems, large technical systems, and engineering design as regards the organization of renewable energy operations (Hughes 1983; Grabowski and Roberts 1996; Perrow 1999a; Coutard 1999; Nightingale et al. 2003; Hurst 2004). Finally, the literature on coherence, alignment, and coevolution between institutions and technologies informs about the interrelations between the dimensions and the performance trade-offs they entail (Nelson 1994; Finger and Künneke 2007; Künneke et al. 2010; Scholten 2013). The framework essentially represents a reshuffling of concepts into a more comprehensive perspective on thinking about institutional design of energy infrastructures. Its innovation lies in the way technical and economic concepts are linked rather than adding fundamental new insights as such. Its relevance also lies in creating awareness for the need for a comprehensive view.

Methodology

SQ1 will be answered through a literature study into engineering design, market design, and coherence and coevolution between institutions and technologies. It will highlight what is known and what is not on the subject matter, also emphasizing the need for a comprehensive framework that should be able to identify, interpret and address future challenges.

SQ2 will be addressed through the building of the framework at the hand of the literature study. Existing insights are linked, reconfigured, and complemented in order to develop the framework. Choices are made regarding what to specifically look at, how to compare across dimensions, and what design knobs can be distinguished. Afterwards, the developed framework is discussed with

Dutch energy experts from EDGaR partners. This ‘reflection’ is not meant to prove or falsify but rather aims to refine; it is part of framework creation. It will provide indications as to the applicability of the framework, the ability to provide accurate outcomes, and suggestions for improvement. Testing and validation occurs via future application to cases (not part of this study).

2.4 Output, Innovation and Relevance

- A framework to systematically and in a reproducible fashion explore the institutional implications of integrating new energy technologies into existing energy infrastructures. Alternatively, it can also investigate the institutional requirements of new market dynamics.
- The development of the CID framework combines *and* aligns system operation and market organization insights. This addresses the current knowledge gap regarding the institutional design of renewable energy infrastructures. It also furthers our understanding of the relationship between the technical, economic, and institutional dimensions of energy infrastructures.
- Research on renewable energy technologies generally relates to their development and deployment. Much less attention is given to the institutional requirements of these technologies once they are put in place. It hence aids in overseeing the broader institutional implications of technical developments and stimulates the awareness of possible institutional lock-ins and path-dependencies in this regard.
- Future application to cases will shed light on in how far new renewable technologies upset energy systems and markets and whether (and which) technical or institutional solutions are most appropriate. Practical beneficiaries of the research are policy makers (insights into the institutional arrangements required to optimize performance) and industry (overview of changes in operational responsibilities and business models).
- The CID framework serves as a guideline for framing the institutional parameters of WP4s agent-based model.

2.5 Research Outline

The report is structured as follows. It starts by elaborating on energy infrastructures as socio-technical systems and the differing design perspectives of engineers and economists (section 3). It also highlights the need for a comprehensive view and the challenge of aligning both dimensions. Then, a comprehensive energy infrastructure design framework is proposed that structures the concepts and insights from both perspectives in a similar fashion and that develops the means to relate these concepts to each other, allowing for the comparison and alignment of techno-operational and socio-economic considerations (section 4). We also critically reflect on the framework proposed, discussing the possibilities and limitations, and conclude with a few possible future research trajectories. Finally, we discuss how the framework should be applied (section 5).

3. Energy Infrastructure Design Perspectives

This section details some basic notions, such as energy infrastructures as socio-technical systems, the different foci that exist in system and market design perspectives, and the necessity of a more integrated design approach in order to lay the foundations for our effort in section 4.

3.1 Energy Infrastructures as Socio-Technical Systems

Over the last decades, energy infrastructures⁵ have undergone profound changes. Traditionally, they were largely operated as vertically integrated public monopolies. 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. In this setting, energy infrastructures were characterized by an engineering culture with a focus on a cost-efficient, reliable and robust service provision (Weijnen and Bouwmans 2006, 127). Since the mid-1990s, however, liberalization, privatization, deregulation, and unbundling led to an increase in the amount and variety of actors involved in the operation of energy infrastructures (Amin 2000) as these infrastructures were cut up into competitive and public segments (Midttun 2001; Newbery 1997). The development of energy infrastructures became based upon “investment signals (whether for the purpose of innovation or capacity expansion) established through market forces” (Weijnen and Bouwmans 2006, 128). In addition, our understanding about the interdependence and co-evolution of technology, industry actors, and institutions shaped a perspective of energy infrastructures as complex adaptive socio-technical systems. Central to this view is that infrastructures are “erected and structured around a certain technical core of physical artifacts [that are] embedded in, sustained by, and interact[ing] with comprehensive socio-historical contexts” (Ewertsson and Ingelstam 2004, 293; Hughes 1983, 465).” The obvious peculiarity of this perspective is that it does not follow an exclusively technical topology of infrastructures (like Barabasi 2003, Newman 2003) but considers the interaction of the integrated physical and social / organizational networks a crucial element in determining system performance (Kroes et al. 2006; Kaijser 2005; Nelson 1994; Geels 2004; Weijnen and Bouwmans 2006). Moreover, the focus is on how technologies, actors, and rules mutually influence and continuously reconstitute each other in a co-evolving manner characterized by lock-in and path-dependency (Scholten 2013; Künneke et al. 2010).

Taking the perspective of energy infrastructures as complex adaptive socio-technical systems, sector performance - commonly measured in terms of availability, affordability, and acceptability (EU 2001) - is the result of the interaction between its techno-operational characteristics, energy market dynamics, and institutional arrangements (Weijnen en Bouwmans 2006; Scholten 2013). More precisely, performance is about how institutions incentivize actors and shape activities in the commodity and monetary flows.

The commodity flow relates to various tangible assets or artifacts that make up the supply chain, such as pipelines, wires, pressure stations, generation plants, etc. and the operational

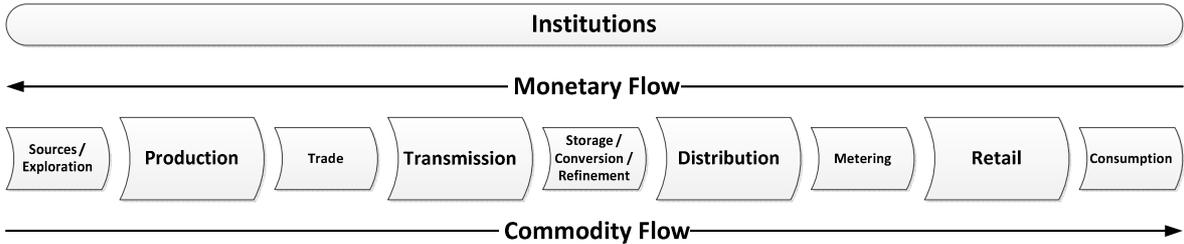
⁵ Energy refers to the energy sources, e.g. fossil fuels (coal, oil, gas), renewables (solar, wind, hydro, geothermal, tidal, waste, and biomass), and alternative energy sources (nuclear), and energy carriers, such as electricity or hydrogen. Infrastructures are defined as “the framework of interdependent 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, citing the US Critical Infrastructure Assurance Office (CIAO)).

activities of the various actors managing the physical flow of energy from producers to consumers. Special attention goes in this regard to the control systems or mechanisms and infrastructure design principles that coordinate the flow of energy, information, or funds through complex transportation and distribution systems and the complementary functioning of the assets.

The monetary flow concerns the economic transactions in energy markets between producers, traders, network companies, retailers, consumers etc. Focus is on actors’ roles, interests, capabilities, and behaviour in energy markets, the nature of transactions between actors, and the market structures within which transactions take place. It is important to note in this respect that markets and business models for energy services are to a great extent shaped by system boundaries and technical characteristics.

Institutions, finally, are about enabling and constraining actor behavior in both flows so as to ensure overall system performance. Whereas the technical operation poses coordination requirements among actors in light of reliability, for example, the economic characteristics of infrastructures require regulation to deal with market imperfections and failures, opportunistic, rent-seeking behaviour, and uncertainty in light of market efficiency and welfare considerations. Finally, energy systems fulfil important societal purposes, often stipulated in public service obligations that these systems need to meet.

Figure 1. Energy infrastructures as complex adaptive socio-technical systems



3.2 Different Design Perspectives

Engineers and economists think about very different things when they talk about design. While the former think about technical systems that need to function reliably and robustly, i.e. the commodity flow, the latter think about markets that need to efficiently and effectively allocate goods and services according to societal needs, i.e. the monetary flow. Moreover, neither of them specifically targets energy infrastructures or large socio-technical systems in their conceptualization of design instead focusing mostly on individual technologies or standard commodity markets. Let us have a closer look at the approaches to system and market design that exist in literature before we put forward our proposal to come to a comprehensive institutional design framework for energy infrastructures.

The Accreditation Board for Engineering and Technology (ABET) defined system or engineering design as:

“the process of devising a system, component, or process to meet desired needs. It is a decision making process (often iterative) in which the basic sciences, mathematics, and engineering sciences are applied to convert resources optimally to meet a stated objective.

Among the fundamental elements of the design process are the establishment of objectives and criteria, synthesis, analysis, construction, testing, and evaluation. It is essential to include a variety of realistic constraints such as economic factors, safety, reliability, aesthetics, ethics, and social impact.” (ABET 1996).

This definition highlights the most important elements of system design. First, it pertains to “the process of defining the architecture, components, modules, interfaces, and data for a system to satisfy specified requirements” of the user (Wikipedia 2014). It is all about deciding on components, how they fit together in the delivery of a good or service, and the design criteria that need to be met in order to satisfy future users (Waldo 2006; Verschuren and Hartog 2005). Second, it refers to the central role of the engineer⁶ in a design process that contains several fundamental steps⁷ and the iterative nature of the decision making process in which a set of resources is converted to optimally reach a certain objective (Hurst 2004). NASA (2008), for example, differentiates between eight steps in the engineering design process of a new product or system; 1: identify the problem, 2: identify criteria and constraints, 3: possible solutions, 4: generate ideas, 5: explore possibilities, 6: select an approach, 7: build a model or prototype, and 8: refine the design. Alternatively, one may follow Verschuren and Hartog (2005) who identify 6 stages that together form one design cycle in the design process. They especially emphasize the importance of evaluating the artefact (product), the goal (plan), the means (process), and their interrelationship. Finally, it also hints at the contradictory design parameters engineering design efforts generally face. Energy systems have to fulfill sometimes conflicting aims: availability and affordability and acceptability. A typical example of this trade-off in energy infrastructures relates to investments in redundant capacity; how much redundant assets are required for reliable operations?

Engineering or system design is situated between the “descriptive and analytical sciences on the one hand, and the aesthetic arts on the other” (McGowan 2000; Verschuren and Hartog 2005). Engineering design therefore has at least three aspects: functionality, anti-failure and aesthetic appeal. Functionality requirements refer to the need for a technology or system to function and to fulfil some specific purpose. Anti-failure or integrity refers to the ability of a technology or system to withstand external shocks in ensuring functionality. Aesthetic requirements, finally, relate to the (pleasing) form of the technology or system. Generally, engineering design focuses on the first two, i.e. on functional design (McGowan 2000). This implies that system design essentially focuses on reliability and robustness as its core values in the design process, as these performance indicators need to be fulfilled regardless of the service a technology or system provides. Of course, reliability and robustness are also measured against the costs needed to reach a minimum or higher level.

Looking at the above, system or engineering design literature seems rather unified in its general approach to designing systems, be they PC software or large technical systems. However, this only accounts for the design process, i.e. how to go about designing, or the evolution of infrastructures through time. Engineering design literature hardly ever describes how large technical systems such as infrastructures are actually designed; there is no ready set of ‘knobs’ that engineers may turn as design variables. This is in large extent due to there simply not being one best way of

⁶ The UK based engineering design lecturer organization SEED Ltd. (Sharing Experience in Engineering Design) noted in its definition of engineering design that “The engineering designer uses intellectual ability to apply scientific knowledge and ensures the product satisfies an agreed market need and product design specification whilst permitting manufacture by the optimum method” (Hurst 2004, 4).

⁷ For a more elaborate discussion of the design process please see: G. Pahl and W. Beitz, 1984, Engineering Design, London, Design Council; recommended by SEED.

handling things; different people or settings require different solutions for similar problems. In addition, “few designers who work in one field can move to another” (McGowan 2000, 2). In other words, insights in one system are hard to transfer. One distinction that seems universal in the field of design science though is the difference between more radical and more incremental changes, whereby the former implies the creation of something new (innovation) and the latter the optimization of something existing (improvement) (Eder 1999; Vincenti 1990; Dasgupta 2009; Verschuren and Hartog 2005).

In economics, market design can imply very different things. Roughly two approaches to designing markets exist. First, neoclassic economic theory defines the characteristics of an ideal market, provides a framework for identifying market imperfections and failures, and allows for designing a desired end state or equilibrium of a market (Correljé and de Vries 2008; Shuttleworth 2000, Newbery 2005a; Joskow 2006; Jamasb and Pollit 2005; Haas et al. 2006; Kwoka 2006). Market design hence focuses on identifying the desired end state that a market should take. While it achieves a strong prescriptive narrative, it does so however by making strong assumptions on actor characteristics and by working at a high level of abstraction, keeping much exogenous or as given (i.e. *ceteris paribus*). It greatly resembles a mathematical thought experiment on how markets ought to be. The downside of this is that NCE theory cannot explain why markets in practice are hardly ever the way the NCE textbooks describe them nor is it able to explain the reform process towards that design. This is usually attributed to political interference or weak (legal) institutions that cannot protect basic property rights etc. in order to ensure market functioning, something that NCE scholars tend to treat as a black box outside the scope of their market models.

Second, institutional economics focuses on behavior of market actors as influenced by institutional arrangements (NIE), processes of institutional change (OIE), and allows for designing policy instruments that guide or enable and constrain actor behavior towards a selected market outcome. Market design hence relates to the purposeful selection of rules, regulations, and procedures to guide the behavior of otherwise undirected market actors so that market outcomes enhance overall welfare. In contrast to NCE, IE considers the body of rules and regulations, norms and values, as being part of the market, i.e. as endogenous. These institutional arrangements are themselves “shaped by a path-dependent interaction between political, [social,] economic, physical [and/or environmental] factors” (Correljé and de Vries 2008, 69) that drive the interests, strategies, and choices of policy makers, firms, consumers, and other actors. IE hence employs a more qualitative research agenda into the context surrounding markets and actors in order to understand why for example some firms vertically integrate, what the effect of a certain allocation of property rights, privatization, or regulation is on market outcomes. The downside of the explanatory power of IE lies in its ability to prescribe, the difficulty to establish causal relations amidst circumstances and the fact that facts may be differently interpreted. Due to its focus on institutional arrangements, IE provides important tools for market design as intended in this chapter.

Most economic works on market design distinguish a number of design variables or ‘knobs’ that policy makers can turn to incentivize actor behavior and a number of structural constraints or context within which the designed market resides. Typically design variables are related to the degree of vertical and horizontal competition, and the process of sector reform. The degree of horizontal competition is related to the number of competitors on a given part of the value chain, for instance energy production or trade. Horizontal competition is related to economic rivalry between different stages of the value chain. For example the legal unbundling between monopolistic networks

and commercial activities like production and trade are intended to increase rivalry. The reform process is influenced by its pace and scope, the gradual change of ownership and decision rights, and the types of allowed contracts or market transactions (Correljé and de Vries 2008; Glachant and Finon 2000; Newbery 2005b; Littlechild 1983; Joskow 2005a; Alexander and Harris 2005). For example, the liberalization of the electricity market posed the choice to move from a market model of monopoly to one of a single buyer, wholesale competition and retail competition. There also was the question which segments to unbundle and/or privatize, what type of regulation is best suited (cost of service or price cap) and or whether capacity mechanisms should be employed to stimulate investments. Key contextual factors are usually what can be assumed as socio-economically, physically-environmentally, and political-institutionally as given (Correljé and de Vries 2008, 71). These are matters like the natural endowment of resources in an area, the level of economic development and growth, or the ideology or political stability in a country. Past policies, practical experiences, and starting conditions can also be added to this list, as may be the intellectual capacity of the policy makers and their mental maps. These contextual factors set the range within which policy makers can choose the design variables, i.e. the solution space available to policy makers. This is not to say that these factors are unchanging. It is to say, however, that there is a difference between those market design exercises that involve the incremental adaptation of market institutions to changing values, technologies, goods or services, or developments in society / markets and those that relate to radical changes that imply a complete redesign of a country's market institutions (though liberalization comes close to such a radical redesign).

3.3 The Need for an Integrated Design Approach

The engineering and economic perspective on energy infrastructures and their design show a great difference in foci. The overview, however, neglects to show that design choices in one dimension affect the other and that this interaction between technology and markets necessitates a more integrated design approach. This necessity becomes clear when diving into the literature on the coherence, alignment, and coevolution of institutions and technologies.

In a number of recent studies (2005-2014), Finger, Künneke, Groenewegen, Menard, Scholten, Perennes, Domanski-Peeroo, and Crettenand studied the relationship between the technical and institutional dimension of several infrastructures (electricity, gas, railways, post). They hypothesized that the economic, social, and technical performance of infrastructures is dependent on the 'degree of coherence' between the technical and institutional scope of control, reaction time, and coordination mechanisms with regard to four technical functions⁸ (interoperability,

⁸ 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/carriers and delivery systems, (e.g. voltage levels and electricity wires), or energy quality/characteristics and application requirements (e.g. natural gas quality and domestic boilers), and regulatory conditions for network access. 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.

Interconnection deals with the "physical linkages of different networks that perform similar or complementary tasks" (Finger et al. 2006, 11-12) and is closely related to technical system boundaries. This includes foremost the facilitation of the connection between local distribution and national and continental transmission networks. Another 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 networks are extended to include new entry and exit points (producers and consumers) or when transmission capacity is increased to allow for additional energy flows.

interconnection, capacity management, and system control) critical for the system to meet user expectations (Finger et al. 2006, 13). By analyzing infrastructures before and after liberalization, they showed that performance⁹ 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. Yet while they concluded that the “technical status of infrastructures influences the opportunities for restructuring and contributes to shape the resulting performance” (Künneke et al. 2010), the exact relationship between technical and institutional organization remained elusive in its specific effect on performance. Nevertheless, the general notion that a certain degree of coherence or alignment between both dimensions is a necessity for ensuring basic infrastructure performance seems established.

The authors are not alone in their argument. According to Garcia et al. (2007, 793-794), ‘technical economies of vertical integration’ may occur in energy infrastructures when physical interdependencies in the production and distribution stages lead to economies of scope and coordination economies, 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). They argue that energy infrastructures may be characterized by such technological economies because of the benefits that may be derived from a “joint optimization of production plant capacity and the size of the transmission system” (Garcia et al. 2007, 794). Another example is the need to balance

Capacity allocation concerns the allocation of “scarce network capacity to certain users or appliances” (Finger et al. 2006, 11-12), i.e. the “allocation of existing resources in order to meet the expected demand” (Künneke and Finger 2007, 309). Issues pertain to questions about the scope and capacity of the network, access rights, and the facilitation of actual access. This implies first of all scheduling energy flows over the network, i.e. unit commitment and capacity utilization, when to start up and shut down generating units, respecting start-up and down rates and their impact on generation efficiencies, and dispatching energy as ordered (Künneke and Finger 2007, 311). This also involves setting up emergency procedures and support services, managing information flows, and handling financial settlements (Amin 2000; Schulman et al. 2004). 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). Finally, it relates to the long-term planning of network and generation capacity, including the choice for fuel technologies to meet future requirements (Künneke and Finger 2007, 310-311). This also relates to the ability to expand or diminish facilities easily and cost-effectively (McCarthy et al. 2157) and adapt to changing circumstances, such as changes in the quantity and type of energy demanded or location of demand (McCarthy et al. 2007, 2157).

Finally, system control “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 energy delivery and operational balancing, i.e. the continuous aligning of supply and demand or regulation of energy flows (voltage or pressure), checking the energy content (quality), real-time disturbance response, and automatic protection to minimize “damage to equipment and service interruptions caused by faults and equipment failures” (Künneke and Finger 2007, 311). Typical concerns are demand fluctuations, intermittency, congestion management, and preventing and responding to equipment outages in order to continue operations (McCarthy et al. 2007, 2155-2158).

⁹ 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.

electricity generation, transportation, and consumption and which requires real-time management. This argument is supported by Joerges (1988, 27) and Kaijser (1994, 52) who 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.”¹⁰

Another example of similar reasoning comes from the literature on ‘Normal Accidents’.¹¹ Looking at technical systems and their potential for failure and recovery and focusing on their organizational causes, Perrow notes an interesting relationship between the interactive complexity and coupledness of technologies in systems and the best suited ‘authority structure’ to handle them (Perrow 1984). First, systems with a high degree of interactive complexity of technical components 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 favoured. Second, tightly coupled systems in which components are strongly interdependent “must be operated through a highly centralized authority structure, with operators reacting immediately using predetermined SOPs”¹² (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.” There is hence an inherent conflict in the authority structure and management style of large-scale technical systems that are both complexly interactive and tightly coupled; 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, electricity and gas infrastructures seem to fall into this category.

Finally, more examples can be found in the literature in which the coherence or alignment framework finds its conceptual grounding, the literature on the co-evolution of institutions and technologies (Abernathy and Utterback 1978; Saviotti 1986, 2005; Saviotti and Metcalfe 1991; Nelson 1994; Perez 2001; Dosi 1982; Murmann 2003; Unruh 2000; von Tunzelmann 2003; Von Tunzelmann et al. 2008) and large technical systems (Hughes 1983; Ewertsson and Ingelstam 2004; Jackson et al. 2007; Geels 2004). There, infrastructure development seems full of examples wherein technical innovations pose new organizational, control, and institutional requirements and wherein existing organizational structures and institutions enable and constrain the technical choices open to pursue, the physical growth of infrastructures, and new possibilities to control network operations.¹³ However, the relationship between the technical and organizational dimension and its effect on

¹⁰ It is tempting at this point to relate levels of centralization of infrastructure operation with levels of vertical integration of infrastructure organization. In this fashion, centralized technical systems would require the specific responsibilities of entities and the nature of their interaction as present under the organizational structure of vertical integration while more decentralized energy systems would require the structure of vertical separation. Vice versa, different organizational structures would imply a preference for different technical systems.

¹¹ 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” (De Bruijne 2006, 56).

¹² 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).

¹³ 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.

system performance stays unclear in these studies. Whereas cause and effect are observed, the transmission mechanisms are far from being fully understood, let alone whether cause and effect are proportional.

In the end, what all of these literatures stress is that a certain degree of alignment between technologies and markets, the design choices and institutions governing these dimensions to be more precise, furthers overall performance (however defined). This also suits well to and supports the perception of energy infrastructures as socio-technical systems where technologies, markets and institutions are heavily interwoven. The stranger it is that we approach the design of those same energy infrastructures so differently. The examples clearly indicate the need and prudence to approach issues regarding the techno-operational and socio-economic design of infrastructures as part of one whole.

4. Towards a Comprehensive Design Framework of Energy Infrastructures

Having detailed energy infrastructures as socio-technical systems, the system and market design literature, and the different foci that exist in both perspectives, we would like to propose a framework for the comprehensive institutional design of energy infrastructures. To this end we first elaborate what we understand system and market design to imply in the context of energy infrastructures and then put forward how we might relate both dimensions to each other in a design exercise.

4.1 Our Engineering Perspective on Energy Infrastructure Design

From an engineering perspective, energy infrastructures relate to the assets or artifacts that make up the supply chain of an energy system, i.e. the tangible objects involved in the operation of an energy system such as pipelines, wires, pressure stations, generation plants, control systems etc. These technologies are not studied as isolated physical artifacts, however, but as technology-as-systems. “Like anything properly called ‘a system’ [, technical artifacts] are part of complex larger wholes of interacting, inter-connected components which support and sustain them” (Ewertsson and Ingelstam 2004, 305).¹⁴ Energy infrastructures, for example, consist out of various components: production facilities, transport and storage means, application technologies etc. Moreover, these various nodes and links need to work together in a complementary fashion and in a certain order. 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).¹⁵ In addition, these nodes are not passive; they “interact with and adapt themselves to their surroundings [and 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). Grabowski and Roberts (1996, 3) wrote in this respect 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.” To ensure complementary functioning of technical components and avoid system errors, engineers follow specific design principles and establish control mechanisms in order to ensure system robustness and operational reliability. Engineers are however not completely free in selecting these design variables; they are shaped by existing technical possibilities available at a certain point in time and place. Moreover, their choice has concrete implications for the decision making space of infrastructure companies regarding daily operations. Let us therefore elaborate what we consider the various layers of system or engineering design.

The first layer relates to the existing conceptual knowledge present in a society and the practical technical possibilities available at a certain point in time and place (level of technology). The control of energy flows, for example, has become increasingly automated because of advancements in ICT-based control technologies. One may also consider good educational institutions that train skilled personal with the necessary know-how and capabilities to be part of this layer for otherwise

¹⁴ Joerges (1988, 24) defines large technical systems (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.”

¹⁵ Rinaldi et al. (2001, 13) 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.

technologies might be unusable or wrongly used. The knowledge base and level of technology are considered to change slowly and emerge spontaneously out of a creative process that is invention and innovation. They are not subject to calculative behaviour or purposeful design of individuals or groups, though policy makers may stimulate education much in the same way as they may promote certain technologies.

The second layer concerns infrastructure design. At its broadest it concerns the perspective on system architecture and asset characteristics, such as whether the system is or should be open or closed (more on this later) and centralized or decentralized in nature and what generation, transport and storage, application technologies (should) make up the assets of the infrastructure. Once decided, attention goes to how infrastructure designers ensure system robustness and plan for eventualities. Key are infrastructure design principles regarding network topology, production, network and storage capacity, redundancy planning, and options for ICT based rerouting. Prominent examples are the N-1 redundancy criterion, wherein a system of N components should be able to continue operations if a single component would randomly fail (Barabasi 2003), or building more resilient network structures that enable rerouting flows. Two categories of disruptive events are commonly distinguished that test the robustness of infrastructures.¹⁶ “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.¹⁷ In addition to carefully choosing topology and capacity etc., the ownership and decision rights with regard to who is responsible for the planning, development, operations, and maintenance of particular assets should be specified. The same goes for who should act or coordinate in cases of emergencies. Such division of ownership and decision rights can usually be found in the technical codes: the system code, network code, and metering code. In the Netherlands, for example, these codes stipulate clearly the specifications that an actor must fulfill in order to obtain a license of supply or who may act as a program responsible party.

The third layer deals with control mechanisms that ensure reliable operations. 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).¹⁸ These may include computerized monitoring systems, routines and emergency procedures, preventive maintenance, switching stations, etc.¹⁹ Well-known examples are the supervisory control and data acquisition systems (SCADA) and energy management systems (EMS)

¹⁶ 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.”

¹⁷ Many causes for malfunctioning, service interruption or quality loss can be distinguished. There are natural disasters (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).

¹⁸ 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.”

¹⁹ Before we become too deterministic, however, it seems proper to point out that reliability is also a matter of careful management. The literature on high-reliable organizations (La Porte and Consolini 1991; LaPorte 1996; Rochlin 1996; Rochlin et al. 1987; Roberts 1993) indicates 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, nuclear reactors, air traffic control, and space shuttles).

(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. 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). Control can be either centralized or distributed (Malik 2000; Bouffard and Kirschen 2008). “In centralized 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). Different control systems imply different ways of coordination between involved actors. It may be fully automated, occasional interaction between many actors, or frequent interactions between a few core actors etc. and top-down or bottom-up in nature. Changes in control can have “important implications for a system’s architecture and performance” (Nightingale et al. 2003, 488). The opposite also holds: changes in the technical composition of an energy infrastructure may necessitate different control mechanisms. As such, they may imply specific responsibilities for entities and may pose more or less stringent coordination requirements among them.

The fourth and final layer concerns firm decision making regarding daily flow activities for ensuring reliability: asset management²⁰, strategic investment²¹, system operation²², and disturbance response²³ (Egenhofer and Legge 2001; IEA 2002; CPB 2004; Joskow 2005b; Joskow and Tirole 2005; von Hirschhausen 2008; McCarthy et al. 2007; Shrivastava et al. 2009). The culmination or aggregation of the system activities of individual actors is expressed in system performance, measured in reliability of operations and system robustness. Special attention could go in this regard to the collective fulfilment of the critical technical functions mentioned earlier. It is important to note that the technological environment (layers 1 and 2a) frames the setting for the design principles and control mechanisms (layers 2b and 3) which in turn enable and constrain actor behaviour on this fourth layer.

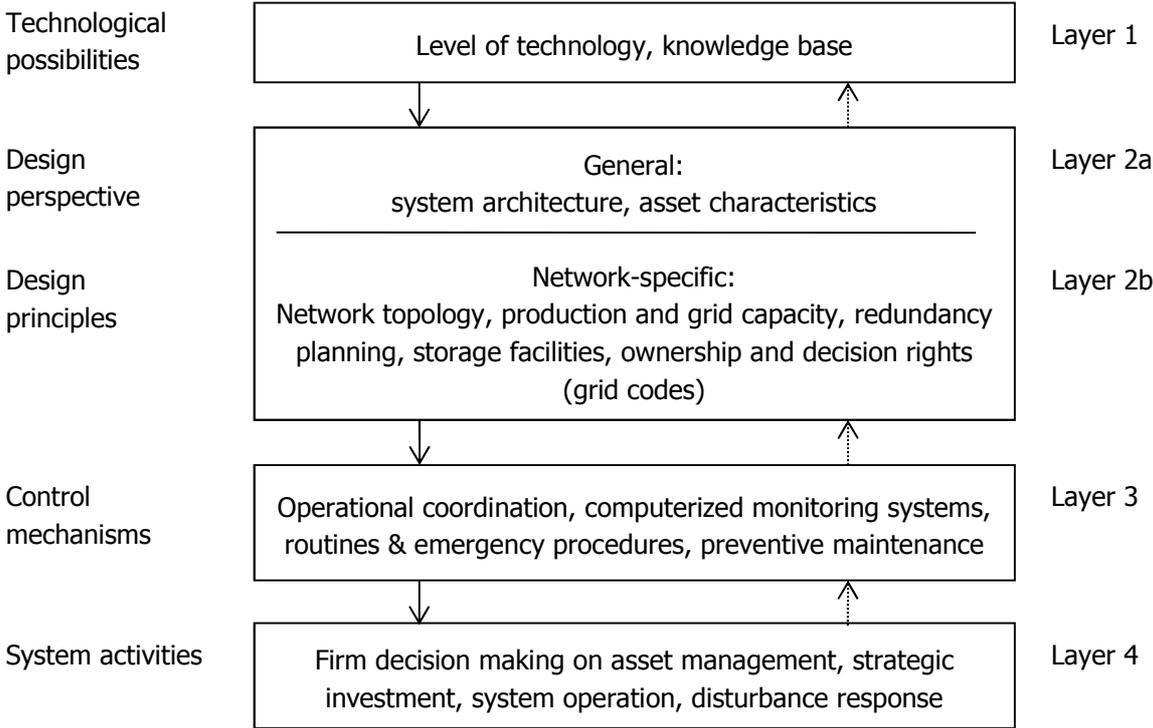
²⁰ The assets or equipment of energy infrastructures simply need to function properly. They should be free of defects and require regular maintenance and timely replacement.

²¹ There should be sufficient investment to ensure that adequate future production and transport capacity is available to meet long-term demand.

²² Focus is on the daily operation of the system as a whole, i.e. the ability to meet demand under normal operating conditions. This relates foremost to the balancing of energy loads and flows across the network in real time, checking pressures and quality, congestion management, and dealing with intermittent production on the supply side and demand fluctuations (seasonal changes, daily quantity, nature, or location) on the other end.

²³ An infrastructure should have the ability to continue operations in the event of equipment outages, or safeguarding system integrity, i.e. “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).

Figure 2. Four layers of design variables in energy infrastructures



Note: The arrows in Figure 2 show ‘solid’ top down relations and ‘dotted’ relations as feedbacks signalling the focus of system design; while in the fullness of time feedback occurs and the system is fully interconnected, when designing infrastructure systems, the logic is that lower levels are embedded in and framed by higher levels (Correlje et al. 2014; Williamson 2000).

Design Principles and Control Mechanisms in the Design of Energy Infrastructure Systems

Systems engineering is generally based around first defining system purposes – what do we want a technical system to do? – and translating them into concrete performance criteria, often a robust design and reliable operations next to the immediate purposes like delivering energy from a to b. Then the ‘givens’ need to be defined. What is open to design and what can be considered part of the given systemic environment (layers 1 and 2a)? Is it a greenfields project or is the design to be embedded within a widely accepted system architecture and are the core assets open to choice? Radical innovations may reshape the fundamentals of a so-called ‘given’ systemic environment while incremental innovations are to be processed within its confines. In addition, the characteristics of the new idea or technology that we are designing for need to be analyzed. Once these parameters are set, engineers may then finally focus on the knobs they may turn so that a systems does what it is intended to do within certain boundary conditions: the design principles of layer 2b and control mechanisms of layer 3. These two cannot be seen independently from each other. The choices made in the two design knobs are then reflected in certain actor behaviour and accompanying network performance that may to greater or lesser extent be similar to the intended performance (layer 4). Big inadequacies are expected to lead to a feedback loop that ushers in a new design effort.

4.2 Our Economic Perspective on Energy Infrastructure Design

Institutions represent the environment in which economic actors operate and by which they are influenced. They are often defined as “the rules of the game” (North 1990) or “credited with establishing patterns of human interaction, by excluding some types of behaviour and encouraging others” (Saviotti 2005, 12-13). 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). Markets require institutions to function efficiently and deliver socially desirable outcomes. The aim of institutional design, in turn, is to ensure that the intended goals of markets or energy systems are met through incentivizing or guiding actor behaviour. In the end, a specific predetermined service is to be provided efficiently and effectively. In this regard, many aspects of institutions can be distinguished. A prominent differentiation is presented by Williamson (2000, 597) who distinguishes between four layers of institutions relevant to market design, and which we have adapted here for our purposes.

The first deals with the informal institutions of traditions, customs, values and norms. These cultural aspects are often not explicitly formulated or codified but are shared convictions in the members of a community. These customs and norms are considered to change slowly and to be not subject to calculative behaviour or purposeful design of individual or groups of economic actors. Instead, informal institutions emerge spontaneously out of the interactions of millions of actors (Correljé et al. 2014). In economic analysis, informal institutions are frequently taken as given and considered important influencing factors on the performance criteria of and formal institutions in a country, market, industry, or firm (Correljé et al. 2014).

The second layer concerns the formal institutions, i.e. the formal state bodies, laws and regulations (the rules of the game). At its broadest, this concerns the constitutional and judicial state institutions present in a polity, i.e. how the political and bureaucratic system works, how state-society relations are framed, and how the rule of law is exercised. From an economic perspective, attention goes more specifically to the relationship between governments and markets or sectors and issues regarding liberalization or public provision, privatization or nationalization, and how competition and sector specific regulation is implemented. To economists, formal institutions should be designed in such a way so as to “provide individual actors with the right incentives to maximize profit and utility or to minimize costs” (Correljé et al. 2014). According to New Institutional Economics literature, the core insights are provided by the theory of Property Rights. “Different systems of property rights (private, public, collective, and common) influence the behavior of actors differently and produce different outcomes” in light of efficient allocation of their scarce resources (Correljé et al. 2014). It is hence of primary importance to carefully assign the right to use, the right to own the costs and benefits of, and the right to sell an asset to public or private actors. Of course, a clear division or allocation of property (ownership and decision) rights requires an independent judiciary and an objective bureaucracy, including the agencies that monitor behavior and enforce rights, as support.

In addition to ownership and decision rights are matters of competition and sector regulation. For competition, the issue is to safeguard free market functioning so that it may generate efficient market outcomes, keeping in mind that market imperfections and failures may necessitate public intervention.²⁴ Important factors in determining the form or degree of competition are the

²⁴ A series of governance failures (information-asymmetry, principal-agent dilemma, policy conflicts, captive government, ideology, trust and stability) needs to be kept in mind whilst deciding regulatory intervention.

possibilities for substitution, the type and cost-structure of the good/service, its position in the life-cycle, the possibilities for liberalization and unbundling. Competition may for example be between electricity and gas infrastructures, between producers operating on the same grid, or via tenders that decide who may provide services (frequently the case in urban transportation). Regulation might be required in light of welfare considerations and specific social goals, public service obligations such as reliability, privacy, sustainability, universal access etc. In both cases, a variety of instruments exist to influence tariffs / prices, profits, quantities, qualities, innovation and investment, market access, number of firms, standards etc. Examples are cost of service or price cap regulation, stipulating access conditions, or setting technical standards. Moreover, regulation should be enforceable and less costly than the market imperfections it tries to correct (Perez-Arriaga 2012).

The third layer concerns the modes of organization that accommodate market transactions, including contractual arrangements and regulatory instruments. The question is whether spot markets, long-term contracts, vertically integrated firms, or regulated state owned enterprises should coordinate an economic transaction. Two approaches shed some light on this matter. First is neoclassical economics where actors make 'make or buy' decisions based on strategic (security, market dominance) and production cost-efficiency (synergies, profit margins) considerations. The benefits of vertical integration have been variously attributed to the elimination of production and cost inefficiencies due to imperfectly competitive intermediate markets; increasing market power in upstream or downstream markets; efficient quality and product differentiation by vertically integrated manufacturers; and reduction of risk and uncertainty in supply. Second is transaction cost economics, where the coordination costs for searching, negotiating, and monitoring contracts are central. Assuming actors possess only bounded rationality and behave opportunistically, insights from Transaction Cost Economics (Williamson 1979) show how specific transactional characteristics (asset specificity, uncertainty, and frequency of the transaction) urge for more or less integrated forms of coordination so transaction costs are minimized. In addition, principal-agent relationship issues (positive agency theory) may be situated on this level. The issue here is how principals may ensure that agents, who have their own interests that may deviate from that of principals, behave according to their interest. How can these different objectives be managed? How to deal with incomplete contracting? The classic example is the relationship between a regulatory agency and a network company of a given energy infrastructure. These issues are often dubbed part of the play of the game; given the rules of the game in layer 2, how do actors coordinate economic transactions?

Finally, the fourth layer relates to short term market activities, company internal decision making on prices, quantities, and investments, business models, and optimization of operation and maintenance. It links to the field of Neo-Classical Economics. The sum of actor activity results in a certain market outcome, usually expressed in terms of the static and dynamic efficiency of markets and/or the effectiveness with which a specific good or service is provided to consumers. In the energy sector, this usually is translated into how the availability, affordability, and acceptability (and increasingly sustainability) of electricity, gas, oil, or heat can be most efficiently achieved. Many public service provisions may be also attached to this list, for example, universal service obligations or safety standards. It is important to note that the institutional environment (layers 1 and 2a) frames the setting for the governance and organizational arrangements (layers 2b and 3) which in turn incentivize actor behaviour on this fourth layer.

Figure 3. Four layers of economic institutions for energy infrastructures



Note: The arrows in Figure 3 show ‘solid’ top down relations and ‘dotted’ relations as feedbacks signalling the focus of market design; while in the fullness of time feedback occurs and the system is fully interconnected, when designing institutional arrangements, the logic is that lower levels are embedded in and framed by higher levels (Correlje et al. 2014; Williamson 2000).

Governance and Organization in the Design of Energy Infrastructure Markets

Institutional design of markets is generally based around first identifying societal values and public interests and translating them into concrete policy goals or performance criteria, in our case efficient and effective provision of energy in light of availability, affordability, and acceptability. The design challenge can be incremental or radical. In case of incremental institutional changes the challenge is to accommodate different values or good/service within the existing institutional environment (layers 1 and 2a). This is about the adjusting the governance and organization of the energy sector in our case (layers 2b and 3). Radical changes in contrast entail a rethinking of institutional fundamentals. In the case of the electricity sector a change towards a strong decentralized provision of electric power by sustainable means of energy production requires a rethinking such a fundamental re-orientation. Afterwards one is ready to investigate: a) the possibilities for competition vis-à-vis public service to ensure efficient allocation, sufficient innovative capacity, and quality (customer satisfaction); b) the possibilities for private and public ownership and decision rights to incentivize actors properly; c) what type of regulation is required to ensure rules the desired performance is achieved; and d) how the various actors may optimally coordinate their transactions. These governance and organizational decisions (layers 2b and 3 respectively) cannot be seen independently from each other. The choices made in the design knobs are then reflected in actor

behaviour and accompanying overall market or sector performance (layer 4) that may to greater or lesser extent be similar to the intended performance with big inadequacies leading to a feedback loop that ushers in a new design effort.

4.3 A Framework for Comprehensive Energy Infrastructure Design

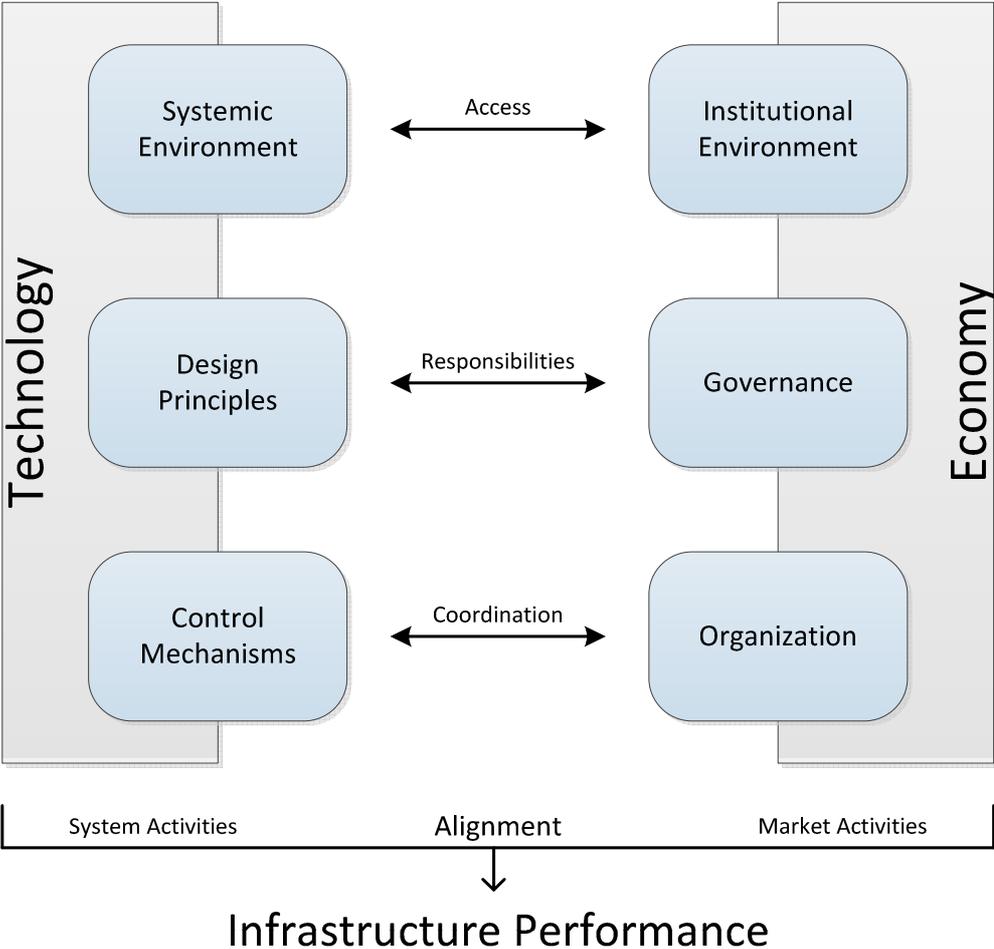
In the above depiction of the two design dimensions of energy infrastructures the importance of consistency in the design of the various layers of a single dimension was noted. Design choices with regard to governance should be in line with the institutional environment within which they are embedded, for example. However, for a socio-technical system, a certain consistency should also exist *between* the same layers of the technical and economic dimensions, according to the literature on coherence between technologies and institutions that we saw earlier. In terms of our discussion above this would imply, for example, that design choices regarding network topology, production and grid capacity, and grid codes, need to be 'aligned' with the governance decisions regarding ownership, competition, and regulation. Let us now have a closer look at how we may relate both dimensions with each other and in this way create a basis for a comprehensive approach of designing the technical and social dimensions energy infrastructures.

Any framework for comprehensive institutional design of energy infrastructures stands or falls with its specification of the interrelation between the technical and economic dimension. But what are the relevant features of an infrastructure technology that matter from an economic perspective and vice versa? Moreover, how do changes in one dimension affect the other? Our proposed framework builds upon five premises.

- The coordination of activities in both dimensions is essential for an infrastructure to perform according to expectations.
- The techno-operational performance is expressed in the reliable and robust functioning of energy infrastructures, irrespective of the good or service being provided.
- The socio-economic performance rests on the efficient and effective provision of a specific good or service, keeping in mind availability, affordability, and acceptability parameters and public service obligations.
- Trade-offs exist between the performance criteria of each dimension and between the dimensions. The minimum conditions of both dimensions must be guaranteed, otherwise either there is malfunctioning (no service provision) or disfunctioning (undesired service is provided).
- The notions applied in system and market design link to a great extent; technical coordination and market transactions are delineated along the same top-down / bottom-up or vertical integration axis, there are ownership and decision rights to be allocated to actors for their systemic operations and market activities, and the general framing of operations and markets seems to be a matter of preference for central planning vs. evolutionary emergence. It is these linkages that allow aligning the systemic and market dimensions of energy infrastructures. Indeed, we would at this point refer to the design variables as the institutions that enable and constrain technical activities, bringing it back into line with our delineation of institutions in the discussion of energy infrastructures as socio-technical systems. They both represent the design 'knobs' that engineers and economists may turn when designing.

The basic idea guiding the comprehensive design framework is that the design variables (institutions) guiding technical operations and institutions enabling market functioning of energy infrastructures need to be consistent, or coherent, with each other. Moreover, they need to align over several layers to ensure overall system performance. The framework is illustrated in Figure 4. The two columns refer back to the overviews of the technical and economic dimensions discussed earlier. The comprehensive design issue is approached at three different levels corresponding to the various layers: between the systemic and institutional environment, between the design principles and governance, and between the control mechanisms and organization. We have termed the various linkages as access, responsibilities, and coordination respectively.

Figure 4. Alignment in the technical and economic design of energy infrastructures



Source: adapted from Künneke 2013, 9.

‘Access’ refers to the generic design of infrastructures. On this level we relate the systemic and institutional environment (layers 1 and 2a of Figures 2 and 3), i.e. the system architecture and asset characteristics to the formal state institutions and perceptions on energy service provision. We make a rough distinction between open access and closed access.

In the technical dimension, closed access is associated with an infrastructure in which only dedicated actors or agencies are allowed to provide a limited number of standardized services. The

technical architecture of a closed system is characterized by centralized hubs that monitor and control critical technical functions, by pre-determined relations between the nodes and links, and by a priori planned and directed intervention efforts by appointed entities. Open access, in contrast, refers to “infrastructures that are accessible for all actors and agencies that are willing and able to contribute to its services” (Künneke 2013, 10). Open access infrastructures rely on protocols, standards or procedures that firms or agencies have to adhere to if they want to participate. It allows for the spontaneous and unanticipated development of the components of an infrastructure, resulting in services that are not foreseen. They may hence provide a broad range of diverse services that are directed towards different groups of users or customers. A good example of both is the difference between how the top-down fashion with which the electricity system has been run for most of the last century and the way decentralized generation technologies might transform this way of working.

In the economic dimension, the notion of open and closed access refers to the traditional state-market dichotomy. Whereas the classic market is competitive, open to new entrants, and dynamic, state controlled provision is often depicted as monopolistic, tightly regulated, and static. The electricity and gas sectors have shifted from one to the other end of this continuum over the course of the last two decades under the process of liberalization, privatization and deregulation. In the traditional approach, energy utilities are vertically integrated monopolies (either regulated or public). As we saw, governments, both through ownership and regulation, control infrastructure planning, construction and service performance, like universal provision, by means of central planning and allocation of funds. In the liberalized approach, infrastructures are cut up into competitive and public segments. On the one hand, industry structure is based on competition and energy markets regarding production, wholesale trade, retail, and additional services such as metering or storage. Here, system operation and expansion are the result of individual company decisions based on the maximization of profits, either under organized tendering or through private energy supply contracts, and investment signals established through market forces. On the other hand, the transmission and distribution network components, with their natural monopolistic features, high sunk costs and externalities, remain publicly owned or regulated.

In the end, the design process should take into account the inherent similarities and differences between technically and economically open and closed systems. In other words, the access of peoples and companies to infrastructure services, either as consumer or as part of the industry, in the technological and institutional environments should be complementary. It is hypothesized in this regard that open systems and market oriented economic approaches are aligned whereas closed system operations match state centric economic approaches.

‘Responsibilities’ refer to the specific design of infrastructures. On this level we relate the technical design principles and market governance arrangements (layer 2b of Figures 2 and 3); essentially we are looking at the way in which ownership and decision rights with regard to technical operations and market transactions (and PSOs) are or should be divided in a specific context of an infrastructure at a specific location and time, given the demands of robust and reliable operations and effective and efficient service provision and given certain general formal institutions and technological architecture.

Technically, there is a specific division of tasks with respect to the monitoring and control of assets and control systems. Which firms, public or private agents (should) have the authority to carry out certain operational tasks, adjust operations according to local conditions and performance

parameters, and intervene in case of emergency? A nice example of this is that TSOs in the Netherlands have balancing tasks and DSOs do not or the specification of which actors are so-called program responsible parties or may obtain a supply license. Another example would be that regulators must approve investments that TSOs wish to make in grid capacity.

Economically, property rights need to be assigned to the companies in the sector. Moreover, given the nature of the good / or service and its intended purpose, decisions on the degree of competition and forms of regulation need to be made. The goal is to deal with possible market imperfections and failures and opportunities of opportunistic behavior that stand in the way of an efficient and effective service provision that also meets public service obligations. A nice example of this is the fact that even after liberalization, networks are still public monopolies while production and retail have opened up to competitive pressures because they have natural monopolistic features and are a strategic facility in ensuring that public interests are met.

In the end, the design process should take into account that the allocation of ownership and decision rights in one dimension does not obstruct the functioning of the other. Moreover, network topology and capacity should be such that it may allow for competition if that is the preferable market structure. In other words, the scope of control of companies to handle their operational responsibilities should be coherent with their role in energy markets, i.e. the scope of ownership over their assets.

‘Coordination’ refers to the interaction between the different actors. On this level we relate the techno-operational coordination and market transactions among actors in realizing a specific good or service (layer 3 of Figures 2 and 3). We assume the general system architecture and formal institutions as given, likewise the division of control and intervention tasks or ownership and decision rights (i.e. the design principles and governance of the sector).

Technically, coordination relates to the nature of interaction among actors involved in an activity (hierarchical, horizontal, or in between). It is dependent on the amount and variety of actors that together manage the assets and operations on the one hand (Scholten 2013) and the speed with which they need to coordinate their efforts / activities on the other (Kunneke et al. 2010) - keeping in mind the given scope of responsibilities and the broader infrastructural and market features such as network complexity and utilization rate, dynamic economic conditions and age of the infrastructure etc. (Scholten 2013). Variations in coordination usually range from centralized forms of management to autonomously operating units (Adler and Shenhar 1990, 30) and are generally based upon differences in “the number of organizational units required for decision-making [...] and the interdependence of those units” (Grabowski and Roberts 1996, 8) and/or the complexity of the interactions involved (Williamson 1979).²⁵

Economically, coordination relates to the nature of transactions (contractual, firm, public), under given property rights, market structure, and regulation. When it comes to distinguishing

²⁵ In this sense, it is believed that centralized or hierarchical organizational structures are suited to facilitating frequent communications and complex interactions among actors in highly interdependent systems because they minimize conflicting interests among entities, put entities in close proximity, create a shared business culture, improve supply chain coordination (avoid capacity-demand-supply balancing issues), facilitate investment in highly specialized assets, and allow for top-level, central control and decision making that has the overview to manage cascading events (Grabowski and Roberts 1996, 3). Decentralized or 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.

between different contractual arrangements among actors, the concept of vertical integration²⁶ (Williamson 1979; Harrigan 1984, 1985; Perry 1989; Joskow 2005a; Ménard and Shirley 2005; Mulder et al. 2005; Mulder and Shestalova 2006) and works on networks of actors (Provan and Kenis 2007)²⁷ prove particularly useful. Without discussing them here in full, four general organizational structures particularly attuned to the operation of energy infrastructures can be roughly distinguished. 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. The pre-liberalization era energy incumbents would be a typical example of this type. Second is 'lead entity' in which several entities have formal responsibility for their part of technical operations but where a single entity acts as a lead organization for key coordination activities. The current role of transmission system operators in many liberalized energy systems comes to mind here. Third is 'common operation'. This more horizontal 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 or have to coordinate for certain control mechanisms while none of the entities has central authority. Forms of community based self-governance of local renewable energy systems might be an example of this type. Fourth is 'incidental coordination', a decentral organizational structure in which entities coordinate only when occasionally required and in such a way that bilateral interaction (based on contracts) between the relevant entities is usually sufficient. The oil downstream sector is an example here.

In the end, the design process should take into account that the nature of coordination, be it top-down vs bottom-up or centralized vs decentralized in the technical dimension or private contracting vs vertical integration or autonomous actors vs a central leading actor in the economic dimension, should not lead to delays or miscommunication between the dimensions. It is hypothesized in this respect that centralized control and vertically integrated firms go together just as decentralized control mechanisms match private market contracting.

Comprehensive Institutional Design

If we combine the insights on the three linkages between both dimensions and the system and market design approaches discussed of sections 3.1 and 3.2, we can formulate a framework for

²⁶ Williamson (1979), for example, differentiates between four types of modes of organization that may coordinate transactions efficiently (based on the asset specificity, uncertainty, and frequency of the transaction in need to be governed): classical contracts in which rights and obligations of all parties are clearly specified, an unified governance structure where coordination resides in one decision making center (a vertically integrated hierarchy or firm), 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 1996, 10).

²⁷ Provan and Kenis (2007) differentiate between four vertical integration strategies to facilitate coordination and cooperation in actor networks. First is a form based on private contracting between the members of a network of organizations (i.e. actors) in a decentralized way where "every organization would interact with every other organization to govern the network" (Provan and Kenis 2007, 233-234). 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.

comprehensive institutional design. A typical socio-technical design challenge arises when a new value, good/service, idea, or technology comes into being and is picked up by actors relevant to the energy infrastructure for possible inclusion in the infrastructure's system or market institutions. Again the first question would be whether a new value, good/service, idea, or technology complements the existing systemic or institutional environment rather than redefines it. Afterwards, decisions need to be taken regarding the governance and organizational choices on the one hand and the design principles and control mechanisms on the other in a coherent fashion, i.e. as described above with regard to access (only for radical changes), responsibilities, and coordination. Calibrating the design 'knobs' occurs within the boundaries set by the institutional and systemic environment and across the dimensions so that they align. Actor behavior under these design constraints finally results in a certain performance, which feeds back to new economic and technical developments and design efforts.

4.4 Reflection and Conclusion

The proposed framework is part of an ongoing research effort into the interrelationship between the technical, economic, and institutional dimension of socio-technical systems. It has come a long way since the first ideas on 'coherence' emerged about ten years ago. The bare bones static comparative analysis between the technical and institutional dimension of infrastructures and its relation to overall system performance has been increasingly operationalized, embedded in the broader literature on co-evolution of institutions and technologies and socio-technical systems, and has now led to hypotheses regarding how to align both dimensions to another within a comprehensive institutional design framework. Nevertheless, there are still several challenges that deserve further attention. Most pertinent to mention has to be that the presented framework in essence only represents a hypothesis of how we may frame comprehensive infrastructure design. A thorough empirical testing, for example, has yet to be undertaken, despite the fact that earlier versions of the coherence and alignment framework have been applied to a few initial case studies (Finger et al. 2006, Künneke 2008, Scholten 2009, 2012; Crettenand and Finger 2013; Perennes 2013; Domanski-Peeroo 2014).

The next urgent matter regards the degree of coherence we should aspire to. The three horizontal linkages between the various layers of the technical and economic dimension make it possible to relate design steps in one dimension to those of another, and hence moving beyond merely optimizing either the system or market design. It, however, does not answer one fundamental question: just how much should both dimensions be coherent?²⁸ In principle an answer is simple; to the extent that a basic level of reliable and robust functioning and effective and efficient service provision can be guaranteed at the same time. In practice, however, the measurement of a degree of coherence has proven to be an operationalization nightmare (Crettenand and Finger 2013). That is not to say that a more qualitative analysis cannot benefit from the structure or lens provided by the coherence and comprehensive design framework. There is also an additional consideration to keep in mind here: a certain degree of incoherence could be important to stimulate technical

²⁸ Especially interesting would be to better understand how differing trade-offs among technical, operational, economic, political, social, and environmental performance criteria relate to varying degrees of coherence regarding access, responsibilities, and coordination and how incoherence may lead to technical innovation and institutional reforms.

innovation and institutional reform.²⁹ Because of this, perfect coherence is generally not perceived to be desirable either. Then again, this should not be much of a problem; it seems rather utopian to believe perfect coherence is attainable in the first place.

Third, the comprehensive institutional design framework, with its focus on the three linkages between the technical and economic dimension, hints at how we may relate one dimension to the other. The next step is to be able to move from one dimension to the other, i.e. derive the design criteria for the institutional arrangements based solely on the technical characteristics of an energy system on each level and vice versa. Inroads have been made into this aspect solely on the level of coordination (Künneke et al. 2010; Scholten 2013). The higher levels remain unexplored country. The added benefit of such an exercise would be that it forces a further operationalization of the concepts thus far presented.

Fourth, more fundamentally, the framework in general seems to be attuned to a more mechanical operation of infrastructures; it features only as a control mechanism at this point. It remains to be seen if this is sufficient to capture the information management that smart grids would require, for example. Should it be treated as a fifth technical function or as a feature that enables new control possibilities for the technical functions? 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?

Fifth, the static CID framework invites moving towards a more dynamic representation of system and market design. In practice design efforts are ongoing, not a one-time exercise; they are a process of continuously readjusting system and market institutions to ensure actors behave in such a way that an infrastructure meets its techno-operational and socio-economic goals.

Finally, the role of actors in bringing about alignment between both dimensions was not discussed in the framework. The framework is attuned to use by academics, policy makers, and engineers in shaping various systemic, economic, and societal actor behaviour so that techno-operational and socio-economic performance is realized. Exactly how these actors respond to governance incentives and design principles is left out. Only the eventual performance can tell whether a design has been successful or not. In addition, the role of actors in technical innovation and changing values and institutions that warrants a design effort in the first place also falls outside the scope of this framework.

To sum up, the proposed CID framework remains untested, insufficiently operationalized, and improperly scrutinized. The ambition is to adapt and enhance the proposed framework by investigating the foundations of the various layers of institutions guiding system operations and market activities, by further operationalizing the interrelationship between the clusters of design variables, i.e. the notions of access, responsibility, and coordination, and by applying the framework to cases (learning by doing). Central effort is the further development of the concept of alignment along the three layers in order to have the ability to identify inconsistencies between market and system designs.

²⁹ 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).

Despite these considerations, we believe the proposed framework presents a careful inroad to comprehensive institutional design of energy infrastructures. As such, the development of the framework has added scientific value in furthering our understanding of the relationship between technologies and economics of energy infrastructures, enhancing our ability to understand the interrelation between design requirements at various levels of abstraction and decision making, and increasing our comprehension of the roles and responsibilities of various entities in maintaining the performance in socio-technical systems. The framework's value also lies more in capturing the relevant considerations within one overview, for providing a structured and reproducible investigation of the techno-operational and socio-economic design criteria, and for presenting (a guiding reasoning for) the design steps to be undertaken. At the very least, the framework provides a useful starting point to further unravel and explore the complex relationship between the technical and economic dimension of energy infrastructures and their combined design.

5. Application of the CID Framework

With the proposed CID framework elaborated, a few final words should go to how the framework might be applied to cases, such as the ECN configurations (WP1), and how it may serve as input for agent-based models, such as developed by TNO (WP4).

Regarding cases, framework application is envisioned to be structured along the following steps:

- I. A description of a country or region's energy sector. This implies detailing a country's systemic and institutional environment within which a future energy system configuration is set to become embedded, the performance criteria that need to be fulfilled, a description of current technologies and accompanying operational practices (design principles and coordination mechanisms), and a description of relevant actors (their business models / interests) and accompanying market governance and organization practices. This can be achieved through a literature study supported by interviews.
- II. A description of cases' technical assets after system integration. The various changes in supply chain components and (control) technologies should be elaborated (how are technologies integrated into existing network (control) architectures). These cases should comprise viable business cases to guarantee their relevance. Together, step I and II set the scene for the analysis.
- III. The identification of operational and market implications of technology integration (changes in actors, operational coordination and responsibilities, markets and business models) and their interpretation in terms of institutional challenges.³⁰ To this end, the insights of the framework are applied to the cases and interviews with industry experts are held to confirm what more and less likely changes are. The aim is to establish an overview of the changing operations and market only. We do not concern ourselves here with limitations of existing institutional boundaries, i.e. existing rules and regulations. This interpretation rests heavily on early adopting countries' experiences and existing insights on operations and markets.
- IV. An investigation of institutional design options and their performance trade-offs (across both dimensions). Emphasis here is on the possibilities to address the challenges highlighted in step 3; special emphasis goes to how design principles, control mechanisms, governance and organization should be changed in order to ensure a reliable operation of energy systems that meets socio-economic performance criteria, and whether the necessary new institutional arrangements require a rethinking of the systemic and institutional environment. In other words, in how far are new opportunities feasible and desirable within the existing operational and market rules and regulations? The outcome should be a listing of the necessary institutional adjustments.

The application of the framework rests partly on literature studies and partly on iterative interviews with policy makers, industry experts, and scholars. The literature plays a key role in identifying the relevant changes in the commodity and monetary flows, institutional challenges, and institutional options. Feedback from industry and policy experts is crucial in determining the importance of the

³⁰ The integration of E-G-H energy systems on the local and regional level may reshape

- a) the actors involved in the Dutch electricity system;
- b) their operational roles and responsibilities (with special attention to distribution network operators);
- c) energy markets and business models for energy services; and
- d) the institutional arrangements required to incentivize a reliable operation of future local and regional energy systems that meets socio-economic performance criteria.

challenges found and in refining and validating preliminary, framework based, institutional recommendations.

Expected Output

- An overview of cases' changes in actors, operational roles and responsibilities, markets and business models, and institutional challenges.
- Overview of the institutional design options that should accompany the system integration cases in a particular country in order to ensure technical, economic, and social performance and the possible institutional adjustments that they necessitate.

Concerning the latter, the framework can serve as a guideline for the institutional parameters of agent-based models. At the very least it provides an overview of what to think about and look at when discussing the institutional design of energy infrastructures. What parameters to take on board? It may also inform about and help operationalize relevant parameters (and associated design options). What aspects are more relevant for the case being modeled; how to model them? It is likely that not all design choices on the vertical columns of Figure 4 are open for reconsideration, for example. In addition, it generates a structured way of thinking about the institutional design of (future) energy infrastructures; it aids in positioning various layers of institutional parameters, allowing linking specific layers to specific actors. Hopefully, it also allows linking (the implications of) technical and economic choices of agents to each other. The greatest downside of the CID framework at this point would be the rather high-level of abstraction and lack of testing. While we cannot do more about the latter at this point, the former can be mended by looking more into the literatures mentioned in the vertical columns (on design principles, coordination mechanisms, governance and organization). This way, detailed questions regarding contracting in a specific energy market could be addressed by the mentioned literature on transaction costs for example. The works on the coherence and alignment between institutions and technologies are also a good starting point to operationalize the concepts of alignment and performance.

References

Abernathy, W. and J. Utterback (1978), 'Patterns of industrial innovation', *Technology Review*, Vol. 80, 41-47.

Accreditation Board for Engineering and Technology (ABET) (1996). Checked 15 May 2014. Available at: <http://www.me.unlv.edu/Undergraduate/coursenotes/meg497/ABETdefinition.htm>

Adler, P.S. and A. Shenhar (1990), 'Adapting your technological base: the organizational challenge', *Sloan Management Review*, Vol. 32, No. 1, 25-37.

Akorede, M.F., Hizam, H. and Pouresmaeil, E. 2010. "Distributed energy resources and benefits to the environment", *Renewable and Sustainable Energy Reviews*, Vol. 14, No. 2, pp. 724–734.

Alexander, I., Harris, C. (2005). *The Regulation of Investment in Utilities: Concepts and Applications*, World Bank Working Paper no. 52, The World Bank, Washington.

Amin, M. (2000), 'National infrastructures as complex interactive networks', in T. Samad and J. Weyrauch (eds.), *Automation, Control, and Complexity: An Integrated Approach*, Chichester: John Wiley and Sons, 263-286.

Amin, S.M. and Wollenberg, B.F. 2005. "Toward a smart grid: power delivery for the 21st century", *IEEE Power and Energy Magazine*, Vol. 3, No. 5, pp. 34–41.

Armstrong, M. and R. Porter, R. 2007. *Handbook of Industrial Organization - Volume 3*. Amsterdam: Elsevier.

Barabasi, A.L. (2003), *Linked: How Everything Is Connected to Everything Else and What It Means for Business, Science, and Everyday Life*, New York: Penguin Group.

Bouffard, F. and D.S. Kirschen (2008), 'Centralised and distributed electricity systems', *Energy Policy*, Vol. 36, 4504-4508.

Correljé, A. and L. de Vries, (2008), 'Hybrid Electricity Markets: The problem of explaining Different Patterns of Restructuring', in F.P. Sioshansie (ed.), *Competitive Electricity Markets: Design, Implementation and Performance*. Elsevier Global Energy Policy and Economics Series, February 2008, ISBN: 978-0-08-047172-3.

Correljé A., Groenewegen J., Künneke R. and D.J. Scholten. 2014. "Design for Values in Economics", In J. van den Hoven, I. van de Poel, and P. Vermaas (eds.), *Handbook of Ethics, Values and Technological Design*. Springer; Dordrecht.

Crettenand, N. and M. Finger (2013), The LAignment between Institutions and technologies in network industries, *Competition and Regulation in Network Industries*, special issue, Vol. 14, No. 2, 106-129.

Dasgupta, S. (2009), *Design theory and computer science* (Vol. 15). Cambridge University Press.

De Bruijne, M.L.C. (2006), *Networked Reliability; Institutional Fragmentation and the Reliability of Service Provision in Critical Infrastructures*, PhD Thesis, defended on 19 June 2006, Delft University of Technology, the Netherlands.

Domanski-Peeroo, A. (2014). *Decentralization and the Water Sector: Institutional Perspectives*; Paris Sorbonne 1, France.

Dosi, G. (1982), 'Technological paradigms and technological trajectories; a suggested interpretation of the determinants and directions of technical change', *Research Policy*, Vol. 11, No. 3, 147-162.

Dutton, K., Thompson, S. and B. Barraclough (1997), *The Art of Control Engineering*. Addison Wesley Longman, Harlow, UK.

Eder, W.E. (1999), 'Designing as an educational discipline', *International Journal of Engineering Education*, 15(1): 32-40.

Egenhofer, C. and T. Legge (2001), *Security of Supply: a question for policy or markets?* Brussels: CEPS.

European Commission (EC) 2001. Green paper; Towards a European Strategy for the Security of Energy Supply. Brussels: European Commission.

EWEA. 2009. *Wind Energy – the facts*. European Wind Energy Association.

Ewertsson, L. and L. Ingelstam (2004), 'Large technical systems: a multidisciplinary research tradition', in M-O. Olsson and G. Sjöstedt (eds.), *Systems Approaches and their Application: Examples from Sweden*, the Netherlands: Kluwer Academic Publishers, 291-309.

EZ (Ministry of Economic Affairs of the Netherlands). 2013. *Energieakkoord* (Dutch Energy Agreement). EZ, The Hague.

Finger, M., J. Groenewegen and R. Künneke (2006), *The quest for coherence between institutions and technologies in infrastructures*, discussion paper, Delft: Delft University of Technology.

Finger, M. and R. Künneke (2007), 'The coevolution between institutions and technology in liberalized infrastructures: the case of network unbundling in electricity and railways', paper presented at the 11th Annual Conference of the International Society for New Institutional Economics (ISNIE), June 21-23 2007, Reykjavik, Iceland.

Garcia, S., M. Moreaux and A. Reynaud (2007), 'Measuring economies of vertical integration in network industries: an application to the water sector', *International Journal of Industrial Organization*, Vol. 25, 791-820.

Geels, F. (2004), 'From sectoral systems of innovation to socio-technical systems: insights about dynamics and change from sociology and institutional theory', *Research Policy*, Vol. 33, No. 6-7, 897-920.

Glachant, J.-M. and Finon, D. (2000). 'Why do the European Union's electricity industries continue to differ? A new institutional analysis'. In: C. Ménard, ed.: *Institution, contracts and organizations: perspectives from new institutional economics*. London: Edward Elgar.

Grabowski, M. and K. Roberts (1996), 'Human and organizational error in large scale systems', *IEEE Transactions on Systems, Man, and Cybernetics*, Vol. 26, No. 1, 2-16.

Groenewegen, J.P.M. (1996), *Transaction Cost Economics and Beyond: Why and How?* Kluwer Academic Publishers, chapter 1.

Haas, R., Glachant, J.-M., Keseric, N. and Perez, Y. (2006). 'Competition in the Continental European Electricity Market: Despair or Work in Progress?' In: Sioshansi, F.P. and Pfaffenberger, W. (eds.) *Electricity Market Reform, An International Perspective*. Amsterdam: Elsevier.

Harrigan K.R. (1984), 'Formulating vertical integration strategies', *The Academy of Management Review*, Vol. 9, No. 4, 638-652.

Harrigan K.R. (1985), 'Vertical integration and corporate strategy', *The Academy of Management Journal*, Vol. 28, No. 2, 397-425.

Hopkins, A. (1999), 'The limits of normal accident theory', *Safety Science*, Vol. 32, No. 2-3, 93-102.

Hughes, T.P. (1983), *Networks of Power, Electrification in Western Society 1880-1930*, Baltimore: Johns Hopkins University Press.

Hurst, K. (2004), *Engineering design principles*. Oxford: Elsevier.

International Energy Agency (IEA) (2002), *Security of Supply in Electricity Markets: Evidence and Policy Issues*. Paris: OECD/IEA.

Jackson S.J., P.N. Edwards, G.C. Bowker, and C.P. Knobel (2007), 'Understanding infrastructure: history, heuristics, and cyberinfrastructure policy', *First Monday* (online peer-reviewed journal), Vol. 12, No. 6, 4 June 2007.

Jamasb, T. and Pollitt, M. (2005), *Electricity market reform in the European Union: Review of Progress toward Liberalization & Integration*, *The Energy Journal European Energy Liberalization Special*, pp. 11-42.

Joerges, B. (1988), 'Large technical systems: concepts and issues', in Mayntz, R. and T.P. Hughes (eds.), *The Development of Large Technical Systems*, Frankfurt am Main: Campus Verlag, 9-37.

Jonker, M. (2010), *Modernization of Electricity Networks; Exploring the interrelations between institutions and technology*, PhD Thesis, defended on 7 September 2010, Delft University of Technology, the Netherlands.

Joskow, P.L. (2005a), 'Vertical Integration', in C. Ménard and M.M. Shirley (eds.), *Handbook of New Institutional Economics*, the Netherlands: Springer, 319-348.

Joskow, P. (2005b), 'Supply Security in Competitive Electricity and Natural Gas Markets'. Cambridge, MA, Paper prepared for the Beesley Lecture in London on October 25, 2005.

Joskow, P. (2006). 'Introduction to Electricity Sector Liberalization: Lessons Learned from Cross-Country Studies'. In: Sioshansi, F.P. and Pfaffenberger, W. (eds.) *Electricity Market Reform, An International Perspective*. Amsterdam: Elsevier.

Joskow, P.L. and J. Tirole (2005). "Reliability and Competitive Electricity Markets." September, (revised). http://econ-www.mit.edu/faculty/download_pdf.php?id=917

Kaijser, A. (2005), 'How to Describe Large Technical Systems and Their Changes over Time?', in G. Jönsson and E. Tengström (eds.), *Urban Transport Development. A Complex Issue*, Springer, 12-19.

Kaijser, A. (1994), *I fädrens spår. Den svenska infrastrukturens historiska utveckling och framtida utmaningar*, Stockholm: Carlssons.

Kaldellis, J.K. and Kapsali. M. 2013. "Shifting towards offshore wind energy—Recent activity and future development", *Energy Policy* 53, pp. 136–148.

Koppenjan J. and J. Groenewegen (2005), 'Institutional design for complex technological systems', *International Journal Technology, Policy and Management*, Vol. 5, No. 3, 240-257.

Kroes, P., M. Franssen, I. Van de Poel and M. Ottens (2006), 'Treating socio-technical systems as engineering systems: some conceptual problems', *Systems Research and Behavioral Science*, Vol. 23, No. 6, 803-814.

Künneke, R. (2008), 'Institutional reform and technological practice: the case of electricity', *Industrial and Corporate Change*, Vol. 17, No. 2, 233-265.

Künneke R. and M. Finger (2007), 'Technology matters: the cases of the liberalization of electricity and railways', *Competition and Regulation in Network Industries*, Vol. 8, No. 3, 303-335.

Künneke, R. and T. Fens (2005), 'Network governance in electricity distribution: public utility or commodity?', paper submitted to the 7th *IAEE European Energy Conference*, European Energy markets in Transition, the Norwegian School of Economics and Business Administration NHH, 28-30 August 2005, Bergen, Norway.

Künneke, R. and T. Fens (2006), 'Ownership unbundling in electricity distribution: the case of the Netherlands', *Energy Policy*, Vol. 35, No. 3, 1920-1930.

Künneke, R., J. Groenewegen and C. Ménard (2010), 'Aligning modes of organization with technology: critical transactions in the reform of infrastructures', *Journal of Economic Behavior & Organization*, Vol. 75, No. 3, 494-505.

Künneke, R.W. (2013), *Critical Infrastructures: aligning institutions and technologies*. Inaugural speech, TU Delft, 27 march 2013, Delft The Netherlands.

Kwoka, John (2006). *Restructuring the US Power Sector: A Review of Recent Studies*, Report Prepared for the American Public Power Association, Northeastern University, November 2006.
<http://www.appanet.org/files/PDFs/RestructuringStudyKwoka1.pdf>

La Porte, T.R. (1996), 'High reliability organizations: unlikely, demanding and at risk', *Journal of Contingencies and Crisis Management*, Vol. 4, No. 2, 60-71.

La Porte, T.R. and P. Consolini (1991), 'Working in practice but not in theory: Theoretical challenges of High-Reliability Organizations', *Journal of Public Administration Research and Theory*, Vol. 1, 19-47.

Littlechild, S. C. (1983). *Regulation of British Telecommunication's Profitability*, Department of Industry, London: HMSO.

Malik, O.P. (2000), 'Control Considerations in a Deregulated Electric Utility Environment', *IEEE Canadian Review*, Vol. 36, 9-11.

McCarthy, R.W., J.M. Ogden and D. Sperling (2007), 'Assessing reliability in energy supply systems', *Energy Policy*, Vol. 35, 2151-2162.

McGowan, P. (2000), *Engineering Design*, Orica Engineering, Melbourne Australia. Available at:
http://www.ncedaust.org/pdf/page_pdfs/19.pdf

Ménard, C. and M. Shirley (eds.) (2005), *Handbook of New Institutional Economics*, New York: Springer.

Midttun, A. (2001), 'De-regulation and reconfiguration of infrastructure industry: theoretical reflections on empirical patterns from Nordic markets', *Journal of Network Industries*, Vol. 2, No. 1, 25-68.

Mulder, M. and V. Shestalova (2006), 'Costs and Benefits of Vertical Separation of the Energy Distribution Industry: The Dutch Case', *Competition and Regulation in Network Industries*, Vol. 1, No. 2, 197-230.

Mulder, M. and Willems, B. 2009. "Borging van publieke belangen in de energievoorziening", In E. van Damme and M. Pieter Schinkel (eds.), *Marktwerking en Publieke Belangen; Preadviezen 2009*, Koninklijke Vereniging voor de Staathuishoudkunde.

Mulder, M., V. Shestalova and M. Lijesen (2005), *Vertical Separation of the Energy-Distribution Industry, An Assessment of Several Options for Unbundling*, The Hague: CPB Document.

Murmann, J.P. (2003), *Knowledge and Competitive Advantage; The Coevolution of Firms, Technology, and National Institutions*, Cambridge: Cambridge University Press.

NASA 2008. Engineering Design Process. Retrieved in May 2014 at:
http://www.nasa.gov/audience/foreducators/plantgrowth/reference/Eng_Design_5-12.html

Nelson, R. (1994), 'The co-evolution of technology, industrial structure, and supporting institutions', *Industrial and Corporate Change*, Vol. 3, No. 1, 47-62.

Netherlands Bureau for Economic Policy Analysis (CPB) (2004), *Better safe than sorry? Reliability policy in Network Industries*, CPB No. 73, The Hague: CPB.

Newbery, D.M. (1997), 'Privatisation and liberalisation of network utilities', *European Economic Review*, Vol. 41, No. 3-5, 357-383.

Newbery, D. (2005a). Refining Market Design, Paper presented at the Conference "Implementing the Internal Market of Electricity: Proposals and Time-Tables" on Friday, 9 September 2005 in Brussels, Sessa, <http://www.sessa.eu.com/public/publications.php>

Newbery, D. (2005b). Electricity Market Reform in the European Union: Review of Progress towards Liberalization & Integration, *The Energy Journal European Energy Liberalization Special*, pp. 155-179.

Newman, M.E.J. (2003), 'The structure and function of complex networks', *SIAM Review*, Vol. 45, 167-256.

Nightingale, P., T. Brady, A. Davies and J. Hall. (2003), 'Capacity Utilization Revisited: software, control and the growth of large technical systems', *Industrial and Corporate Change*, Vol. 12, No. 3, 477-517.

North, D.C. (1990), *Institutions, Institutional Change and Economic Performance*, Cambridge: Cambridge University Press.

Pahl, G. and W. Beitz (1984), *Engineering Design*. London, Design Council.

Perennes, P. (2013), 'Need for Coherence between Institutions and Technologies: The Example of Uncertain Train paths in France', *Competition and Regulation in Network Industries*, special issue, Vol. 14, No. 2, 130-150.

- Perez, C. (2001), 'Technological change and opportunities for development as a moving target', *CEPAL Review*, Vol. 75, 109-130.
- Pérez-Arriaga, I. J. (2013). *Regulation of the Power Sector*. Springer London.
- Perrow, C. (1984), *Normal accidents: Living with high risk technologies*, New York: Basic Books.
- Perrow, C. (1999a), *Normal Accidents, Living With High-Risk Technologies*, Princeton: Princeton University Press.
- Perrow, C. (1999b), 'Organizing to reduce the vulnerabilities of complexity', *Journal of Contingencies and Crisis Management*, Vol. 7, No. 3, 150-155.
- Perry, M.K. (1989), 'Vertical integration: determinants and effects', in R. Schmalensee and R.D. Willig (eds.), *Handbook of Industrial Organization*, Volume 1, 183-255.
- Provan, K. and P. Kenis (2007), 'Modes of Network Governance: Structure, Management, and Effectiveness', *Journal of Public Administration Research and Theory*, Vol. 18, 229-252.
- Rinaldi, S.M., J.P. Peerenboom and T.K. Kelly (2001), 'Identifying, Understanding, and Analyzing Critical Infrastructure Interdependencies', *IEEE Control Systems Magazine*, Vol. 21, No. 6, 11-25.
- Roberts, K.H. (ed.)(1993), *New Challenges to Understanding Organizations*, New York: Macmillan.
- Rochlin, G.I. (1996), 'Reliable organizations: present research and future directions', *Journal of Contingencies and Crisis Management*, Vol. 4, No. 2, 55-59.
- Rochlin, G., T.R. La Porte and K. Roberts (1987), 'The selfdesigning high-reliability organization: aircraft carrier flight operations at sea', *Naval War College Review*, Vol. 40, 76-91.
- Saviotti, P. (1986), 'Systems theory and technological change', *Futures*, 773-786.
- Saviotti, P. (2005), 'On the co-evolution of technologies and institutions', in M. Weber and J. Hemmelskamp (eds.), *Towards Environmental Innovations Systems*, Heidelberg: Springer, 9-32.
- Saviotti, P. and J.S. Metcalfe (1991), *Evolutionary Theories of Economic and Technical Change*, Reading: Academic Publishers.
- Schleicher-Tappeser, R. 2012. How renewables will change electricity markets in the next five years. *Energy policy*, 48, 64-75.
- Scholten, D.J. (2009), 'Matching Institutions to Technologies; The Case of a Transition to Hydrogen in the Netherlands', *Paper presented at the ECPR Conference*, Potsdam 10-12 September 2009.

Scholten, D.J. (2012), *Keeping an Eye on Reliability; the Organizational Requirements of Future Renewable Energy Systems*. PhD Thesis. Delft University of Technology. 29 June 2012. Delft: Eburon.

Scholten, D.J. 2013. "The Reliability of Energy Infrastructures; the Organizational Requirements of Technical Operations", *Competition and Regulation in Network Industries*, special issue, Vol. 14, No. 2, 173-205.

Seyfang, G. and A. Smith (2007), "Grassroots innovations for sustainable development: Towards a new research and policy agenda," *Environmental Politics*, vol. 16, no. 4, pp. 584–603.

Shrivastava, S., K. Sonpar and F. Pazzaglia (2009), 'Normal Accident Theory versus High Reliability Theory: A resolution and call for an open systems view of accidents', *Human Relations*, Vol. 62, No. 9, 1357-1390.

Shuttleworth, G. (2000). *Opening European Electricity and Gas Markets*, NERA, 2000.

Stoft, S. (2002), *Power System Economics*. Wiley-Interscience and IEEE Press, Piscataway.

Unruh, G.C. (2000), 'Understanding carbon lock in', *Energy Policy*, Vol. 28, No. 12, 817-830.

Verschuren, P., & Hartog, R. (2005), 'Evaluation in design-oriented research', *Quality and Quantity*, 39(6): 733-762.

Vincenti, W.G. (1990), *What engineers know and how they know it: The John Hopkins University Press* Baltimore.

Von Hirschhausen, C. (2008), 'Infrastructure, regulation, investment and security of supply: a case study of the restructured US natural gas market', *Utilities Policy*, Vol. 16, No. 1, 1-10.

Von Tunzelmann, N. (2003), 'Historical coevolution of governance and technology in the industrial revolutions', *Structural Change and Economic Dynamics*, Vol. 14, 365-384.

Von Tunzelmann, N., F. Malerba, P. Nightingale and S. Metcalfe (2008), 'Technological paradigms: past, present and future', *Industrial and Corporate Change*, Vol. 17, No. 3, 467-484.

Waldo, J. (2006) *On System Design*. Essay Series Published by Sun Labs. Available at: <http://scholar.harvard.edu/files/waldo/files/ps-2006-6.pdf>

Walker, G. and P. Devine-Wright, (2008), "Community renewable energy: What should it mean?," *Energy Policy*, vol. 36, no. 2, pp. 497–500.

Weick, K.E. (2004), 'Normal accident theory as frame, link and provocation', *Organization & Environment*, Vol. 17, No. 1, 27-31.

Weijnen, M.P.C. and I. Bouwmans (2006), 'Innovation in networked infrastructures: coping with complexity', *International Journal of Critical Infrastructures*, Vol. 2, No. 2/3, 121-132.

Wikipedia 2014. Engineering design and system design. 15 May 2014. Available at:

http://en.wikipedia.org/wiki/Engineering_design_process

http://en.wikipedia.org/wiki/System_design

Williamson, O. (1979), 'Transaction cost economics: the governance of contractual relations', *Journal of Law and Economics*, Vol. 22, 233-261.

Williamson, O.E. (2000), The New Institutional Economics: Taking Stock, Looking Ahead, *Journal of Economic Literature*, Vol. XXXVIII, 595-613.