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DOI
10.3390/su8121291

Publication date
2016

Document Version
Final published version

Published in
Sustainability

Citation (APA)
Scholten, D., & Kunneke, R. (2016). Towards the Comprehensive Design of Energy Infrastructures. *Sustainability*, *8*(12). https://doi.org/10.3390/su8121291

sustainability

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Article

Towards the Comprehensive Design of Energy Infrastructures

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Academic Editors: Michiel Heldeweg, Ellen van Bueren, Anna Butenko, Thomas Hoppe, Séverine Saintier, Victoria Daskalova and Marc A. Rosen
Received: 26 September 2016; Accepted: 13 November 2016; Published: 9 December 2016

Abstract: Energy infrastructures are increasingly perceived as complex, adaptive socio-technical systems. Their design has not kept up; it is still fragmented between an engineering and economic dimension. While economists focus on a market design that addresses potential market failures and imperfections, opportunistic behavior, 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. As such, we are ill-equipped to identify, interpret, and address the challenges stemming from technical innovations, e.g., the integration of renewable energy technologies, and institutional changes, e.g., liberalization or new forms of organization like cooperatives, which often have interrelated operational and market implications. In response, this paper proposes a more comprehensive design framework that bridges the engineering and economic perspectives on energy infrastructure design. To this end, it elaborates the different design perspectives and develops the means to relate design variables of both perspectives along several layers of abstraction: the form of infrastructure access of actors, the division of responsibilities among actors, and type of coordination between actors. The intention is that this way system and market design efforts can be better attuned to each other and we further our understanding and conceptualization of the interrelationship between the techno-operational and economic-institutional dimensions of energy infrastructures. The framework 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; system design; market design; comprehensive institutional design

1. Introduction

Over the last decades, energy infrastructures have been increasingly perceived as complex adaptive socio-technical systems whose performance—commonly measured in terms of availability, affordability, and acceptability [1]—rests on the continuous interaction between its techno-operational characteristics, energy market dynamics, and institutional arrangements [2–6]. The way we approach the design of energy infrastructures, however, has remained rather fragmented in nature. On the one side, are engineers who consider 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 [7–12]. On the other side, are economists, policy makers, and legal experts who focus on market designs that address potential market failures and imperfections, opportunistic behavior, and social objectives [13–17]. They think more about energy markets that need to efficiently and effectively allocate goods and services according to societal needs. Moreover, neither of them specifically targets energy infrastructures or large socio-technical systems in their conceptualization of system or market design.

The fragmented nature of energy infrastructure design is troublesome in at least two ways. First, the two design logics may be complementary, but may also be at odds. They may generate different, or even conflicting, outcomes. 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, creating a more decentralized mode of organization, while the technical operation remained that of a vertically integrated monopoly controlled from a central control room [18]. System operation and market organization hence represent contradictory modus operandi. As a result, market interests and activities of actors can start to conflict their operational roles and responsibilities. Second, and more fundamentally, it is generally unclear what design choices or developments in one dimension imply for the other. Currently we lack the means to express ex ante the implications of engineering choices on market designs of energy infrastructures and vice versa. This hinders determining how we should, for example, interpret and address the interrelated systemic and market challenges raised by new renewable energy technologies, such as the feed-in of solar PV based electricity from thousands of households and the intermittency of large-scale wind, or new forms of organization, such as distributed generation and energy cooperatives.

A new and more comprehensive design framework is necessary that bridges the engineering and economic perspectives on energy infrastructure design. Ideally, it would provide scholars and practitioners the means to explore the implications of (planned or emerging) technical and economic changes in a structured manner, by positioning implications in an easy-to-use and comprehensive overview, and possess a vocabulary to relate concepts and implications to another. This would enable them to oversee the economic implications of technical developments (and vice versa) and stimulates awareness of lock-ins and path-dependencies in this regard. Moreover, it would allow them to identify and assess design options across both dimensions.

This paper proposes such a comprehensive design framework. Building upon literature on socio-technical systems, system and market design, and energy infrastructures, it reconfigures existing insights in order to relate the design variables of both perspectives along three layers of abstraction: the form of infrastructure access of actors, the division of responsibilities among actors, and type of coordination between actors. The intention is to be able to attune system and market design efforts to each other so that we may adequately identify, interpret, and address interrelated operational and market challenges to energy infrastructure performance. In doing so we not only further our understanding and conceptualization of the interrelationship between the techno-operational and economic-institutional dimensions of energy infrastructures, but also help practitioners come with regulatory responses to innovation in energy systems, be they decentralized energy technologies or the embedment of new forms of organization such as cooperatives. One word of caution: this paper only proposes a comprehensive design framework; application to cases is left for follow-up research.

The paper is structured as follows. It starts by elaborating energy infrastructures as socio-technical systems and the differing design perspectives of engineers and economists (Section 2). This also highlights the need for a more comprehensive view. Next, a comprehensive design framework is proposed that structures the core 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 in a design effort (Section 3). We then critically reflect on the framework proposed, discussing the possibilities and limitations of its application and point out future research trajectories (Section 4). Finally, Section 5 concludes.

2. Energy Infrastructure Design Perspectives

2.1. Energy Infrastructures as Socio-Technical Systems

Energy infrastructures comprise all the sources, technologies, actors and institutions involved in the production, transportation, consumption and management of energy (see Figure 1). Energy refers to the sources, e.g., fossil fuels (coal, oil, and gas), renewables (solar, wind, hydro, geothermal, tidal, waste, and biomass), 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 (...)" [19] (p. 13, citing the US Critical Infrastructure Assurance Office (CIAO)). Technically, they consist of various nodes and links. The nodes represent the entities and installations that produce, trade, store, refine, sell, and consume energy, like wellheads, power plants, refineries, transformer stations, and all sorts of electric appliances. The links make up the long-distance and local networks that transport and distribute energy between the nodes, like pipelines, electricity grids, and oil tankers. Typically, a distinction is made between upstream (exploration, production, and trade), midstream (transportation, refinement, and storage) and downstream (distribution, metering, retail, and consumption). The necessity for all nodes and links to function complementary represents a crucial aspect for the infrastructure to deliver energy from producers to consumers in a reliable and robust fashion. Economically, energy infrastructures were traditionally run as vertically integrated public monopolies, with the notable exception of oil, where private multinationals play a great part. 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. Since the mid-1990s, however, liberalization, privatization, and unbundling led to an increase in the amount and variety of actors and markets involved in energy infrastructures as these infrastructures were cut up into competitive and public segments [20–22]. "Investment signals (...) established through market forces" [5] (p. 128) determine production, trade, and retail while sector specific regulation is applied to networks because of their natural monopolistic features.

Over the last decades, energy infrastructures have been increasingly perceived 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" [23] (p. 293). The obvious peculiarity of this perspective is that it does not follow an exclusively technical topology of infrastructures [24,25] but considers the interaction of the integrated physical and social/organizational networks a crucial element in determining system performance [2–5,26,27]. 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. In this light, energy infrastructure performance—commonly measured in terms of availability, affordability, and acceptability [1]—is the result of the interaction between its techno-operational characteristics, energy market dynamics, and institutional arrangements [6,28]. More precisely, performance is about how institutions and technical options 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 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 [29]. The existing technology (and access to it) sets the boundary conditions of the technically and operationally feasible. It determines the options actors have. Not all assets might be available, for example, and operations may be dependent on ICT systems for smooth coordination among actors.

The monetary flow concerns the business models of producers, traders, network companies, retailers, consumers, etc. and the economic transactions in energy markets between them. Focus is on actor interests, capabilities, and behavior in energy markets, the nature of transactions between actors, and the market structures within which transactions take place. Institutions or "the rules of the game" enable and constrain actor behavior [30] in the monetary flow. The economic characteristics of infrastructures require regulation to deal with market imperfections and failures, opportunistic, rent-seeking behavior, and uncertainty in light of market efficiency and welfare considerations. Moreover, energy systems fulfill important societal purposes, often stipulated in public service obligations.

Agency is retained through the individual decisions that bounded rational actors can make. In the short term, the combination of decisions of the individual actors in both flows, within the boundaries set by technical options and institutional environment, ultimately determines overall performance. Generally, it is hypothesized that a certain degree of coherence or alignment between the organization of the systemic and market dimensions furthers adequate performance [31]. In the long term, the accumulation of individual activities can lead to an overhaul of the technical and institutional boundaries.

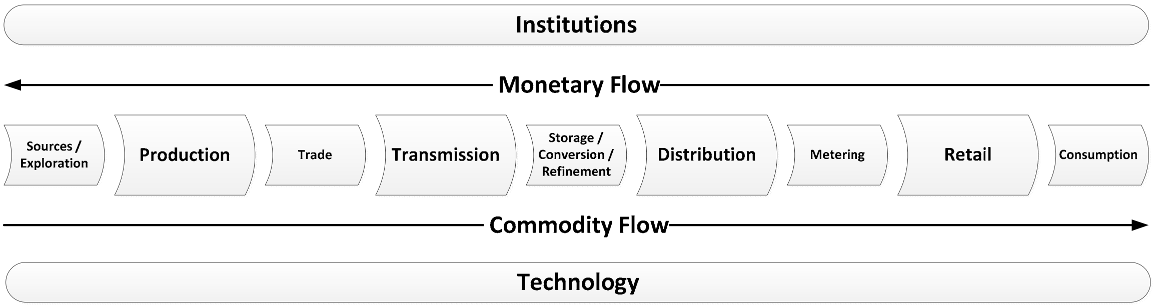

Figure 1. Energy infrastructures as complex adaptive socio-technical systems.

2.2. *Different Design Perspectives*

In stark contrast to the perspective of energy infrastructures as socio-technical systems stands the fragmented nature of their design. While engineers think about technical systems that need to function reliably and robustly, i.e., the commodity flow, economists 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 socio-technical systems in their conceptualization of system or market design. Consequently, no noteworthy effort is made to leave their disciplinary confines or relate the design of both dimensions. To show this, we will briefly discuss what system and market design encompass and how their insights are applied in general and to energy infrastructures in particular.

2.2.1. System Design

The relevant body of knowledge on system design regarding energy infrastructures can be found in roughly two corners. First, the literature directly on the topic of system or engineering design [8,11,12,32–36] describes what system design is and how to go about designing technologies and systems. Second is the literature on Large Technical Systems (LTS), Normal Accidents and High Reliable Organizations that investigates how technical systems such as energy infrastructures function and manage to avoid failures, i.e., manage to be reliable and robust [7,9,10,29,37,38]. It has a more practical orientation yet generates interesting generalizable insights. Let us address them in turn.

A general description of system or engineering design has been put forward by the Accreditation Board for Engineering and Technology (ABET):

> *"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"* [32].

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 [39]. 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 [11,12]. A distinction in the field of design science is usually made between innovations and improvements in this regard. The former imply the creation of something new and the latter the optimization of something existing [11,33–35]. Another typical distinction is often made between open and closed systems, i.e., whether a system allows interactions between their internal elements and the environment or isolated from its environment [36].

Second, it refers to the central role of the engineer in an iterative design process that contains several fundamental steps through which a set of resources is converted to optimally reach a certain objective [10]. NASA [40], 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 [11] who identify six stages that together form one design cycle in the design process. Interestingly, this approach to designing technologies and systems is considered applicable to such diverse products as PC software and large technical systems.

Finally, it also hints at the contradictory design parameters engineering efforts generally face. A typical example of a trade-off in energy infrastructures involves investments in redundant capacity: how much redundant assets (affordability) are required for reliable operations (availability)?

While the system design literature is useful for describing the general approach or design process, it does not present a general set of "knobs" that engineers may turn as design variables. Better insights into how energy infrastructures are actually designed can be found in the literature on Large Technical Systems (LTS), Normal Accidents and High Reliable Organizations. Covering a wide range of topics, including technology choice, system architecture, prevention of small and large scale accidents, and operational control and organization, they highlight a number of key design variables [7,9,10,29,37,38]. In order to design a robust system, network topology, production and grid capacity, redundancy planning and storage facilities seem of crucial importance. A typical example would be the choice of reinforcing existing grids or utilize storage capacity to handle daily load fluctuations or the intermittency effect of renewables. Regarding reliable operations, the nature of coordination, the use of computerized monitoring systems, routines and emergency procedures, preventive maintenance and managerial strategies are key design options [41–45]. In this literature, the choice for more top-down or bottom-up means of control is a frequent point of discussion. Joerges [46] (p. 27), for example, differentiates 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." A similar example comes from Perrow who notes an interesting relationship between the interactive complexity and coupledness of technologies in systems and the best suited "authority structure" to handle them [47–50]. 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, and allow for top-level, central control and decision making that has the overview to manage cascading events, among others [37] (p. 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 [37] (p. 3). The flexibility allows actors to address accidents immediately at the root of the problem (before they cascade) and without the need to wait for higher-level approval. Despite this focus on organizational aspects of operational design, the conceptualization of system design does not touch energy markets; design focuses on the organization of operations only.

2.2.2. Market Design

According to the National Bureau of Economic Research [51] (p. 1) market design "examines the reasons why market institutions fail and considers the properties of alternative mechanisms, in terms of efficiency, fairness, incentives, and complexity". It concerns the practical organization of markets and design of market institutions, usually with options situated along the state-market axis.

Market design research is influenced by ideas from micro-economics, industrial organization, and institutional economics. Neoclassic economic theory (NCE) enables defining 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 [14–16,52–56]. While it achieves a strong prescriptive narrative, it does so by making strong assumptions on actor characteristics and by working at a high level of abstraction, keeping much exogenous or given (i.e., ceteris paribus). The downside is that NCE theory finds it difficult to explain why markets in practice are hardly ever the way the NCE textbooks describe them. This is usually attributed to political interference, 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. Industrial organization concerns "the workings of markets and industries, in particular the way firms compete with each other" [57] (p. 3) and the "determinants of firm and market organization and behavior" [58]. It focuses on firm strategies in imperfectly competitive markets (not the ideal types of the neoclassical approach), real-life conditions such as entry barriers, imperfect information and transaction costs, and regulatory and antitrust policy in an effort to limit negative effects on overall welfare [59–62]. Institutional economics (IE), finally, focuses on behavior of market actors as influenced by institutional arrangements [30,63,64], processes of institutional change [65,66], and allows for designing policy instruments that guide or enable and constrain actor behavior towards a selected market outcome [67]. Market design hence relates to the purposeful selection of rules, regulations, and procedures to guide the behavior of market actors. 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" [16] (p. 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 inability to prescribe, the difficulty to establish causal relations amidst circumstances and that facts may be differently interpreted.

Combined, these works on market design distinguish a number of interrelated design variables or "knobs" that policy makers can turn to incentivize actor behavior in (energy) markets and a number of structural constraints within which the market resides that needs to be taken into account whilst designing. Typically design variables are the degree of vertical and horizontal competition, the type of ownership and decision rights, necessary regulatory measures, the type of contracting and the process of sector reform (pace and scope) [13,16,52,55,68]. Key contextual factors are usually what can be assumed as socio-economically, physically-environmentally, and political-institutionally as given [16] (p. 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 design variables, i.e., the solution space available to policy makers.

Looking at applications of market design insights to energy infrastructures we can recognize these considerations clearly. Typical energy infrastructure related topics are the regulation of natural monopolies, liberalization of wholesale and retail markets, privatization, ensuring public service obligations, stimulation of innovation, promoting/integrating renewable technologies [17,56,61,69–72]. For example, the liberalization of the electricity market posed the choice to move from a public monopoly model 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 was best suited (cost of service or price cap) and or whether capacity mechanisms should be employed to stimulate investments. Technology also features here as an important boundary condition that sets the possibilities for energy markets. The necessity to balance electricity grids instantaneously, for example, requires the presence of standing reserves and balancing markets. Next to such fundamental design exercises as liberalization, which essentially implies a complete redesign of a country's market institutions, more common market design exercises tend to involve incremental adaptations of market institutions to changing values, technologies, goods or services, or developments in society/ markets. Fine-tuning regulatory instruments and policy mechanisms to promote renewable energy can be considered examples here.

2.2.3. The Need for an Integrated Design Approach

Despite the abundance of literature on the technical and economic dimensions of socio-technical systems and their interrelation, system and market design show a great difference in foci. In light of our view of energy infrastructures as socio-technical systems the fragmented nature of energy infrastructure design is troublesome in two main ways.

First, the two design logics may be complementary, but may also be at odds. System and market design may generate different, or even conflicting, outcomes. 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, creating a more decentralized mode of organization, while the technical operation remained that of a vertically integrated monopoly controlled from a central control room [18]. System operation and market organization hence represent contradictory modus operandi. As a result, market interests and activities of actors can start to contradict their operational roles and responsibilities.

Second, and more fundamentally, it is generally unclear what developments or 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 how we should, for example, tackle the interrelated systemic and market challenges raised by new renewable energy technologies. Should we employ a technical or market based solution to address a specific challenge? Intermittency of wind can be handled by storage and extra capacity, for example, but also through energy markets that guide producers to less production in times of negative prices, i.e., severe overproduction, or secondary balancing markets.

The lack of literature on the direct topic necessitates looking elsewhere for inspiration on how to relate both design dimensions to each other. The main sources of inspiration are the works that also underpin parts of the socio-technical systems perspective: those on coherence and coevolution of institutions and technologies and large technical systems. They investigated in depth the relationship between both dimensions and how they affect each other and system performance.

The literature on the co-evolution of institutions and technologies [26,27,73–81] and large technical systems [7,23,82] can be considered to the first to have focused on the relationship between technologies and institutions. They are full of examples of infrastructure development wherein technical innovations pose new control requirements and open up new market possibilities and wherein institutional changes redefine the technical choices open to pursue and possibilities for market competition and public-private ownership. However, while the relationship and mechanisms of transfer between the technical and economic dimension are richly illustrated, there is no formal conceptualization of these relationships beyond co-evolutionary terminology. As such, while we can understand cause and effect, there is no measure of in how far technology and institutions are aligned and what effect this may have on system performance.

Building upon these works, Finger, Künneke, Groenewegen, Ménard, Scholten, Perennes, Domanski-Peeroo, and Crettenand studied the relationship between the technical and institutional dimension of several infrastructures (electricity, gas, railways, post) in a number of recent studies (2005–2015) [6,18,28,31,83–90]. 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 functions critical for the system to meet user expectations (interoperability, interconnection, capacity management and system control) [85] (p. 13). By analyzing infrastructures before and after liberalization, for example, they showed that performance differed because institutional changes were not matched by technical ones; 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 [85]. More importantly, in follow-up studies, the three mechanisms (scope of control, reaction time, and coordination mechanisms) were utilized in aligning institutional arrangements to the technical characteristics of infrastructures [6,28]. Even though they did not focus on design as such, this gives hope that the three mechanisms may be of use in relating design variables.

3. Towards a Comprehensive Design Framework for Energy Infrastructures

The discussion of the energy infrastructure design perspectives has highlighted their fragmented nature, but also introduced the necessary concepts to build a comprehensive design framework. To move forward, we first elaborate what we understand system and market design to comprise within the socio-technical systems view. We structure the design variables of both perspectives in a similar manner into a hierarchy of embedded layers of design decisions from the general and abstract to the specific and practical (inspired by the four layers of institutions of Williamson [64]). This reconfigures existing insights, sorting the design variables, and makes them comparable between the systemic and market dimension. Afterwards, we put forward how we propose to relate both dimensions on all layers and discuss implications for their design. The core idea is that the same layers in both dimensions revolve around similar concepts and/or design knobs: access, responsibility and coordination (inspired by the works on coherence and coevolution of institutions and technology). Finally, we briefly discuss the application of the framework.

3.1. Our Engineering Perspective on Energy Infrastructure Design

As we saw, 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 understood as isolated physical artifacts, 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" [23] (p. 305). These components 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" [5] (p. 125), impacting the "error propensity of the system" [37] (p. 3). 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 (see Figure 2).

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 institutes that train skilled personnel with the necessary know-how and capabilities to utilize the technology to be part of this layer. The knowledge base and level of technology are considered to change slowly and emerge spontaneously out of a creative invention process. They are not subject to calculative behavior or purposeful design of individuals or groups, though policy makers may stimulate innovation and education.

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 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 [24], or building more resilient network structures that enable rerouting flows in case of routine events like maintenance works or major disruptions such as blackouts. In addition to carefully choosing topology, 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.

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" [29] (pp. 477–478). These may include computerized monitoring systems, routines and emergency procedures, preventive maintenance, switching stations, etc. Well-known examples are the supervisory control and data acquisition systems (SCADA) and energy management systems (EMS) [19] (p. 14). Control mechanisms can help reroute energy flows on short notice but also significantly improve the allocation of system traffic on the longer term [29]. Control can be either centralized or distributed [91,92]. "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" [29] (p. 488). Different control systems imply different ways of coordination (and division of responsibilities) between involved actors and can have "important implications for a system's architecture and performance" [29] (p. 488).

The fourth and final layer concerns firm decision making regarding daily flow activities for ensuring robustness and reliability [93–100]. One concern is asset management: assets or equipment of energy infrastructures simply need to function properly; they should be free of defects and require regular maintenance and timely replacement. Another concern is strategic investment: there should be sufficient investment to ensure that adequate future production and transport capacity is available to meet long-term demand. Third is system operation: meeting demand under normal operating conditions concerns 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. Last is disturbance response: operations need to continue in the event of equipment outages; this relates to "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" [85] (p. 4). 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 fulfillment of the critical technical functions as developed by Finger and Kunneke [31]: interoperability, interconnection, capacity management, and system control. 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 behavior on the fourth layer.

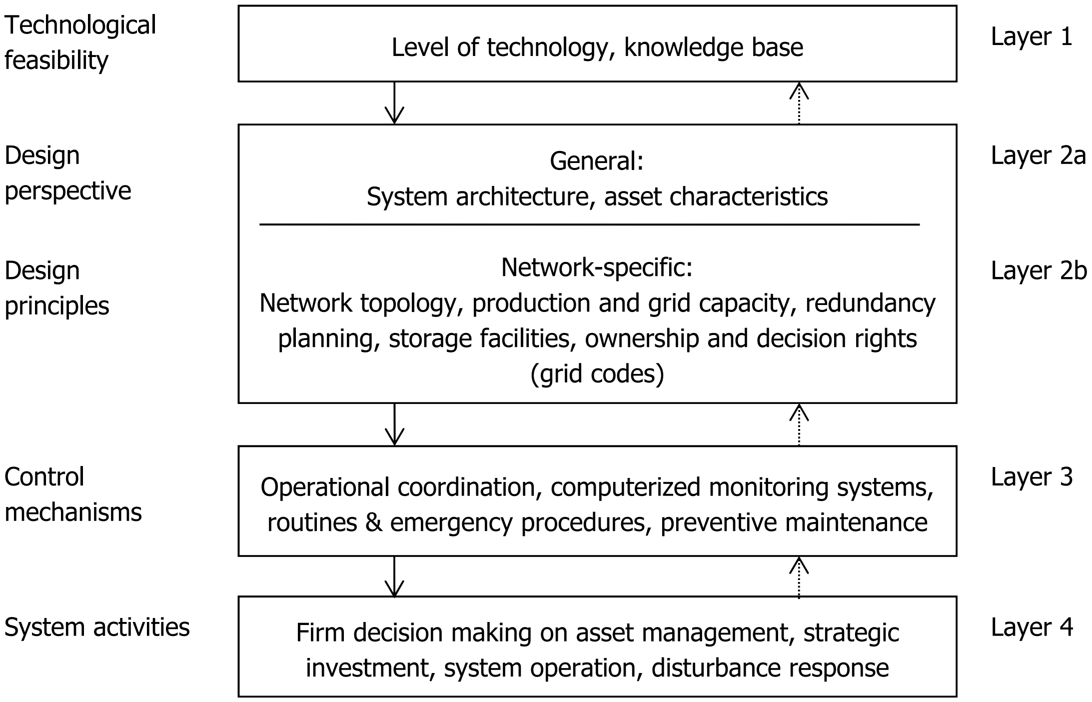

Figure 2. Four layers of design variables in energy infrastructures. Note: The arrows show "solid" top down relations and "dotted" relations as feedbacks signaling the focus of system design; while in the fullness of time feedback occurs and the system is fully interconnected, when designing infrastructure systems, the logic is that lower levels are embedded in and framed by higher levels.

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

Systems engineering generally starts with defining system purposes 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 greenfield project where core assets are open to choice or is the design to be embedded within a widely accepted system architecture? 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 system 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 behavior 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.

3.2. 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" [30] or "credited with establishing patterns of human interaction, by excluding some types of behaviour and encouraging others" [75] (pp. 12–13). 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 behavior. 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 [64] (p. 597) who distinguishes between four layers of institutions relevant to market design, and which we have adapted here for our purposes (see Figure 3).

The first deals with the informal institutions of traditions, customs, norms and values. These cultural aspects are often not explicitly formulated or codified but rather shared convictions by members of a community. They are considered to change slowly and not subject to calculative behavior or purposeful design of individual or groups. Instead, informal institutions emerge spontaneously out of the interactions of millions of actors [101]. In economic analysis, informal institutions are frequently taken as given and considered important influencing factors on the formal institutions of a country and on what adequate performance criteria for markets, industries, and firms are [101].

The second layer concerns the formal institutions, i.e., the "rules of the game", such as the official state bodies, laws and regulations. At its broadest, it entails how the political-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 governance of markets and sectors by governments. Formal institutions should be designed to "provide individual actors with the right incentives to maximize profit and utility or to minimize costs" and in this way contribute to overall welfare [101] (p. 4). Three core design issues stand out: competition, ownership and regulation. For competition, the issue is choose the right modality and to safeguard free market functioning (through competition policy) so that it may generate efficient market outcomes, keeping in mind that market imperfections and failures may necessitate public intervention. Important factors in determining the form or degree of competition are possibilities for liberalization and unbundling, possibilities for substitution, the type and cost-structure of the good/service, and a good/service's position in the life-cycle. Next is the allocation of private vs. public ownership and decision 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 [101] (p. 4). 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 ownership and decision rights requires an independent judiciary and an objective bureaucracy, including the agencies that monitor behavior and enforce rights, as support. Sector-specific regulation, finally, is required in light of welfare considerations, for example to correct market imperfections, and specific social goals, public service obligations such as sustainability, privacy, universal access etc. A variety of instruments exist to influence tariffs/prices or profits, quantities and qualities, innovation and investment, market access, number of firms, standards etc. A series of governance failures (information-asymmetry, principal-agent dilemma, policy conflicts, captive government, etc.) needs to be kept in mind whilst deciding regulatory intervention. Moreover, regulation should be enforceable and less costly than the market imperfections it tries to correct [17].

The third layer concerns the "play of the game", given the rules in layer 2. Attention goes to the contractual arrangements among actors, i.e., the modes of organization that accommodate market transactions. The question is whether spot markets, long-term contracts, vertically integrated firms, or regulated state owned enterprises should coordinate a transaction [63,102–108] 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. In addition, "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, or when intermediate markets involve high transaction costs [109]. Second is transaction cost economics, where the coordination costs for searching, negotiating, and monitoring contracts are central. High levels of asset specificity, frequent interactions, and complex negotiations, for example, would suggest vertical integration. In addition, principal-agent relationship issues 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. Typical examples are the relationship between regulatory agencies and network companies and the phenomenon of incomplete contracting.

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. The sum of actor activity results in a certain market outcome, usually expressed in terms of static and dynamic efficiency 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 behavior on this fourth layer.

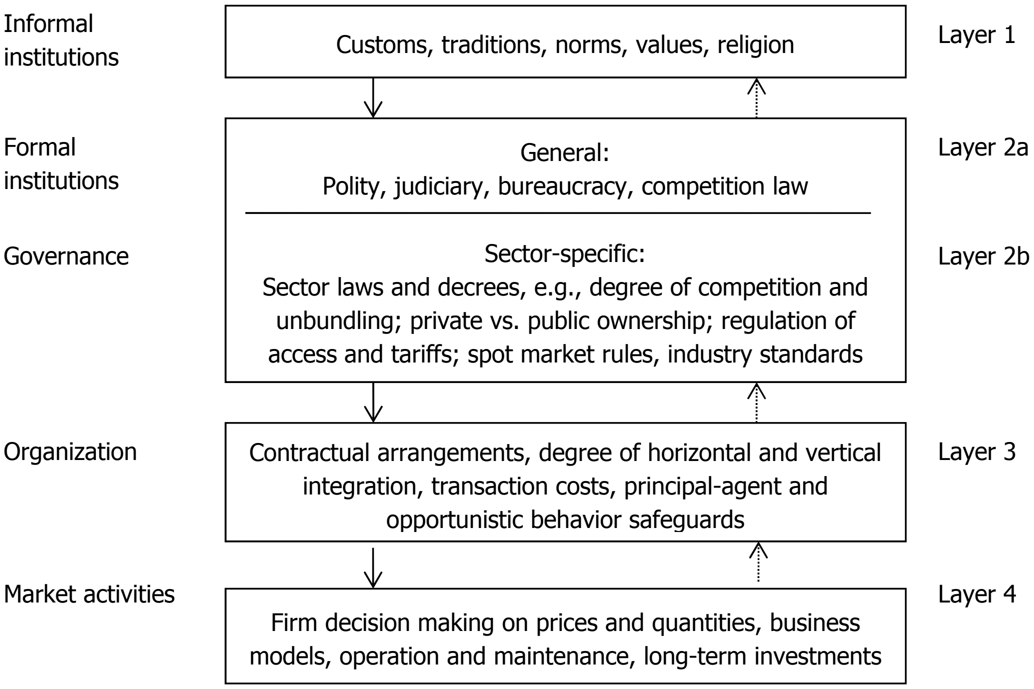

Figure 3. Four layers of economic institutions for energy infrastructures. Note: The arrows in Figure 3 show "solid" top down relations and "dotted" relations as feedbacks signaling the focus of market design; while in the fullness of time feedback occurs and the system is fully interconnected, when designing institutional arrangements, the logic is that lower levels are embedded in and framed by higher levels.

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 (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 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 behavior 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.

3.3. 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 if design choices are not to be at odds with one another. 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 competition, ownership 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 design of energy infrastructures stands or falls with its specification of the interrelation between the technical and economic dimension. However, 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 and how to capture this? 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 there is either malfunctioning (no service provision) or disfunctioning (an undesired service).
- The notions applied in system and market design link to a great extent; technical coordination and market transactions are delineated along the same central–decentral/vertical integration axis; both operational and market activities require a similar allocation of responsibilities, i.e., division

of control/intervention tasks and ownership and decision rights; 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.

The basic idea guiding the comprehensive design framework is that the design variables guiding technical operations and institutions enabling market functioning of energy infrastructures need to be filled in in a consistent fashion. 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 overview of the commodity and monetary flow 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. The grouping of layers 1 and 2a (level of technology and design perspectives and the formal and informal institutions) is in line with our earlier distinction between radical and incremental design challenges; it helps separate common design exercises from fundamental overhauls or green fields projects.

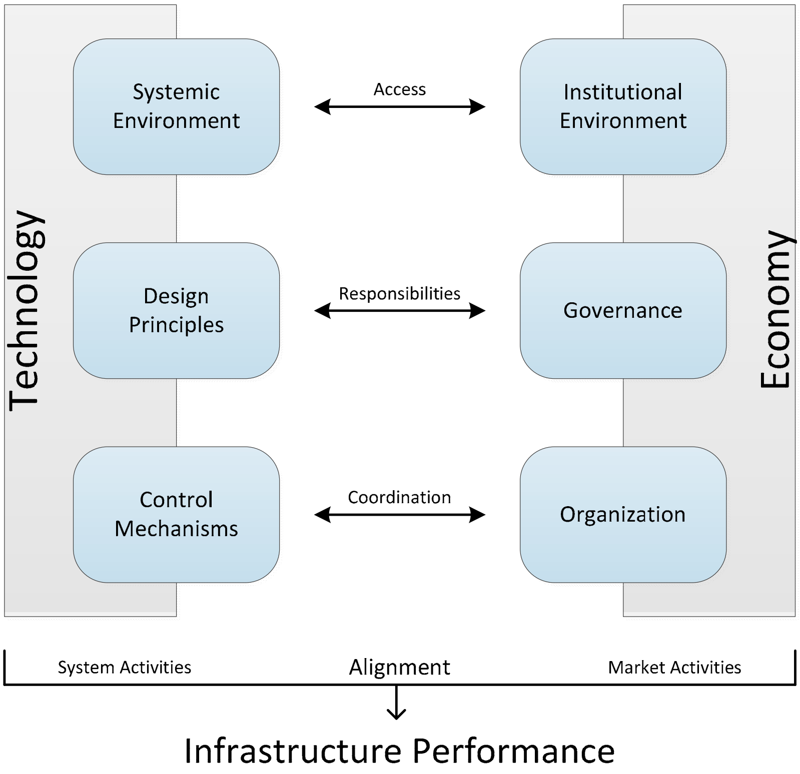

Figure 4. Alignment of the technical and economic design of energy infrastructures. Source: adapted from Künneke [87] (p. 9).

"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 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" [87] (p. 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 infrastructure components and provides a potentially broad range of services directed towards different users. 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. In the traditional approach, energy utilities are vertically integrated monopolies (either regulated or public). Governments, through ownership and regulation, control infrastructure planning, construction and service performance by means of central planning and allocation of funds. In the liberalized approach, infrastructures are cut up into competitive (production, wholesale and retail trade and metering and storage services) and public segments (transmission and distribution networks). In the competitive segments, individual company decisions are based on maximization of profits, either under organized tendering or through private energy supply contracts, and investment signals established through market forces. In the end, the design process should take into account the inherent similarities and differences between technically and economically open and closed systems. There is no need for developing a system open to contributors if market policy is not allowing other parties than the incumbent. 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 control and intervention tasks regarding technical operations and ownership and decision rights concerning market transactions (and public service obligations) are or should be divided at a specific location and time within the systemic and institutional context. Technically, there is a specific division of tasks with respect to the choice and management of assets and control systems. Which firms, public agents or private agents (should) have the authority to carry out certain operational tasks, may decide on investments in new assets and intervene in case of emergency? A nice example of this is that the transmission system operator in The Netherlands has balancing tasks and the distribution system operators 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 in grid capacity that the transmission system operator wishes to make. Economically, specific ownership and decision rights are assigned to companies as part of broader sectoral decisions regarding competition, privatization and regulation. 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 responsibilities in one dimension does not obstruct the functioning of the other. Network topology and capacity, for example, should be such that they allow for competition if that is the preferable market structure. In other words, the scope of control of companies to handle operational responsibilities should be coherent with their role in energy markets.

"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 systemic and institutional environment as given, likewise the design principles and governance of the sector. Technically, coordination relates to the nature of interaction among actors involved in an operational activity. Variations in coordination usually range from centralized forms of management to autonomously operating units [110] (p. 30) and are generally based upon differences in "the number [and heterogeneity] of organizational units required for decision-making (. . .) and the interdependence of those units" [37] (p. 8). The complexity of the interactions and network involved and the speed with which they need to coordinate their efforts can also be added to this list [6,28]. Economically, coordination relates to the nature of transactions under given property rights, market structure and regulation. When it comes to distinguishing between different contractual arrangements among actors, the concept of vertical integration was already noted. The question is whether spot markets, long-term contracts, vertically integrated firms, or regulated state owned enterprises are the appropriate mode of organization. We may also distinguish different modes of network governance along these lines [111]. In the end, the design process should take into account that the nature of coordination, be it centralized vs. decentralized in the technical dimension or private contracting vs. vertical integration 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 in Sections 3.1 and 3.2, we can formulate a framework for comprehensive design. A typical socio-technical design challenge arises when a new 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 design 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, the calibration of design "knobs" occurs within the boundaries set by the institutional and systemic environment. 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. This is the most crucial aspect in any comprehensive design exercise vis-à-vis system and/or market design: maintaining the coherence not only between the design choices on the various layers, but also 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.

3.4. Framework Utilization

With the proposed comprehensive design framework elaborated, a few final words should go to the purpose and utility of the framework. The framework's purpose lies in attuning system and market design efforts so that we may better identify, interpret, and address the interrelated operational and market challenges to energy infrastructure performance. Especially the transition towards renewable energy is a topical contender for framework application [112]. How to arrange the feed-in of solar PV based electricity from thousands of households and the intermittency of large-scale wind, or new forms of organization such as cooperatives? Its utility stems from its ability to explore the implications of a techno-operational or economic-institutional change in a structured manner, by positioning implications in an easy-to-use and comprehensive overview, and its offering of a vocabulary to relate concepts and implications to another. This enables academics and practitioners to oversee the economic implications of technical developments (and vice versa) and stimulates awareness of lock-ins and path-dependencies in this regard. It also allows them to identify and assess possible design options across both dimensions. This way the framework aids in finding regulatory responses to the energy system innovations mentioned above. A brief illustration of how the framework can be applied at the hand of a few steps clarifies this point:

I. The application starts with a description of a country's or region's energy sector. This implies detailing the systemic and institutional environment, the performance criteria that need to be fulfilled, a description of current technologies and accompanying operational practices (design principles and coordination mechanisms), a description of relevant actors (business models, interests), and the relevant market governance and organization practices.

II. Next is a description of the intended or emerging techno-operational or economic-institutional change (new value, good/service, idea, or technology) under investigation. On what layer of which dimension does the change occur? What elements are added or replaced? For example, energy cooperatives are new forms of organization among private actors [113] while smart meters are new control mechanisms for operating the system that are added to existing assets [114]. Together, Steps 1 and 2 set the scene for Steps 3 and 4.

III. We then turn to the interpretation of operational and market implications of the change under investigation (assess related changes in actors and business models, operational roles and responsibilities, market organization and governance). What other layers are affected and how? For example, cooperatives are likely to affect the operational responsibilities and coordination between them and network companies and require specific regulation to clarify their roles in energy markets. Likewise, smart meters raise issues over the control of private data and enable business models that use metering data among other things. The result of this step should be a comprehensive overview of implications positioned on the various layers of the framework's dimensions.

IV. Finally, we turn towards investigating design options and their performance trade-offs (across both dimensions). Focus is on the possibilities to address the implications highlighted in Step 3; special emphasis goes to how design principles, control mechanisms, governance, and organization should be changed in accordance with each other in order to ensure a reliable operation of energy systems that meets socio-economic performance criteria. Where are tensions between design options? How could they be overcome? Do new operational and institutional arrangements require a rethinking of the systemic and institutional environment itself? Cooperatives may need to be explicitly incorporated in network codes, for example, bringing tensions between the free spirit that drives these initiatives and the responsibilities they have towards non-members that are affected by them. The outcome should be an overview of the techno-operational and economic-institutional design options, their performance trade-offs, and the degree to which both dimensions align.

4. Discussion and Reflection

The previous section proposed a first, careful inroad to how we may frame the comprehensive design of energy infrastructures. The framework presented a reconfiguration of established system and market design concepts, placing them into the perspective of energy infrastructures as socio-technical systems, and structured them along three layers of abstraction: the form of infrastructure access of actors, the division of responsibilities among actors, and type of coordination between actors. This enables relating the design variables of both perspectives to each other. In turn, the framework opens the way to attune system and market design efforts, limiting the risk that suggestions are at odds with each other. It also furthers our understanding and conceptualization of the interrelationship between the techno-operational and economic-institutional dimensions of energy infrastructures, so that we may estimate what design choices and/or developments in one dimension imply for the other and stimulate awareness of lock-ins and path-dependencies in this regard. As such, it enables us to adequately identify, interpret, and address operational and market challenges to energy infrastructure performance. For example, the system integration of new renewable energy technologies may bring new operational and market challenges and opportunities. The framework would allow addressing these in a structured fashion by identifying what issues would arise on which layers of both dimensions, giving the means to interpret their impact on the various design variables of the layers, and suggest possible design options based on the underlying system and market design literature whilst relating possible impacts among the dimensions.

Nevertheless, the framework remains untested and insufficiently operationalized and scrutinized, even though it builds upon established insights. The following challenges deserve further attention.

The most urgent matter regards the degree of alignment 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 system or market design. It, however, does not answer one fundamental question: just how much should both dimensions be coherent? 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, varying degrees of coherence regarding access, responsibilities, and coordination result in different trade-offs among technical, operational, economic, political, social, and environmental performance criteria. Moreover, a certain degree of disalignment could be important to stimulate technical innovation and/or institutional reform [115]. When everything is tightly aligned, so the reasoning goes, necessary adjustments to new developments might face stronger opposition. Hence, perfect alignment is generally not perceived to be desirable either. In addition, the measurement of a degree of coherence between institutions and technology has proven to be an operationalization nightmare [89]. That is not to say that a more qualitative analysis cannot benefit from the structure or lens provided by the comprehensive design framework. In any case, a measure of what constitutes smaller and wider divergences, where little divergence would imply manageable alterations and bigger divergences are to be avoided, would need to be established.

Second, the three linkages between the technical and economic dimension propose how we may relate one dimension to another. 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 [6,28]. 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.

Third, more fundamentally, the framework seems attuned to a more mechanical operation of infrastructures. It remains to be seen if this is sufficient to capture the information management that smart grids would require, for example. Should ICT technologies be treated as a feature that enables new control possibilities or as something that radically reshapes system architecture?

Fourth, the static 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 design and market institutions to ensure actors behave in such a way that an infrastructure meets its techno-operational and socio-economic goals.

Fifth, 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; how they may shape actor behavior in order 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 institutions that warrants a design effort in the first place also falls outside the scope of this framework.

The last consideration regards the transferability of the framework to other infrastructures, i.e., its generalizability. We built the framework for energy infrastructures, having the upcoming and past challenges to energy infrastructure design in mind, while noting the difference between the holistic socio-technical systems perspective and fragmented design approaches. Consequently, the construction of the framework followed the specific characteristics of oil, gas, electricity and heat systems to fill in what “knobs” may be turned as design variables and what alignment, in terms of “access”, “responsibilities”, and “coordination”, concretely refers to. Many of the framework’s concepts and system and market design insights, however, seem equally applicable to other traditional infrastructures such as telecommunications and public transportation, especially from the economic dimension. Indeed, the earlier works on socio-technical systems, coherence and alignment, and coevolution between institutions and technologies already analyzed a diversity of infrastructures. Replacing some peculiarities of energy with those from another sector, especially on the technical side, should hence be feasible, at least in our opinion. An investigation into the generalizability of the framework is hence more than warranted.

5. Conclusions

This paper proposed a comprehensive design framework that bridges the engineering and economic perspectives on energy infrastructure design. By restructuring insights on system and market design and placing them within the perspective of energy infrastructures as socio-technical systems, a first, careful inroad to how we may relate design variables of both dimensions at various levels of abstraction was established, opening up the way to the comprehensive design of energy infrastructures. At the very least, the framework provides a useful starting point to further conceptualize and explore the complex relationship between the technical and economic dimension of energy infrastructures and their combined design. This way we may better estimate what design choices and/or developments in one dimension imply for the other and stimulate awareness of lock-ins and path-dependencies in this regard. At its best, it captures the relevant design considerations within one overview, presents the means to relate the design variables of the systemic and market dimension, and provides a guide on how to design. This would enable us to identify, interpret, and address (interrelated) operational and market challenges to energy infrastructure performance, and help find the regulatory responses to energy system innovations that this Special Issue is after.

Nevertheless, the framework remains untested and insufficiently operationalized and scrutinized. Regarding the former, first applications to cases (local heating, smart meters, and power sector reform) to assess its utility and refine it are currently underway. Thus far, the value of the framework in providing a comprehensive overview that can identify and interpret operational and market challenges in energy infrastructures is looking promising. The matter of addressing them in design efforts has yet to be properly investigated. Regarding the latter, improvements can be made regarding the operationalization of the desired degree of alignment between the system and market design, its static nature, the role of agency in the framework, the conceptual incorporation of ICT, and further operationalization of what exactly changes in one dimension imply for the other. Most urgent is the need to further develop the concept of alignment between the design variables of both dimensions along the three layers, i.e., along the notions of access, responsibility and coordination, in order to have the ability to identify inconsistencies between market and system designs.

Acknowledgments: This research has been financed by a grant from the Energy Delta Gas Research (EDGaR) program, and a grant from The Netherlands Organization for Scientific Research (NWO) under the TRAPESES research program. Many thanks also go to the organizers of this Special Issue, especially for their efforts in hosting several sessions at the European Consortium for Political Research (ECPR) 6th Standing Group on Regulatory Governance Biennial Conference, Tilburg University, The Netherlands, 6–8 July 2016.

Author Contributions: Daniel Scholten and Rolf Künneke both conceived the paper and carried out the research together. Daniel Scholten took the lead in writing the paper with Rolf Künneke giving frequent input on draft versions. All authors have read and approved the final manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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