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Organizing Future Energy Systems for Reliability

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The reliability of energy infrastructures has organizational requirements. However, the perception of energy infrastructures as socio-technical systems has not yet made its way into the planning for future energy systems; while the technical and economic aspects of new renewable energy infrastructures are well-researched, the organizational structure required for their reliable functioning is not. So what are the organizational requirements of new renewable energy systems; and how to know?

The Organizational Requirements of Reliability and the Challenge of an Energy Transition

Modern economies greatly depend on the well-functioning of energy infrastructures. Without a reliable supply of energy, industrial machinery, household appliances, agricultural equipment, transportation, communications, and PCs all come to a halt. Consequently, policy makers and industry incumbents have traditionally kept a close eye on reliability, i.e. "the ability of the system to deliver the product (or service) transported over the network without interruption and without deterioration of its quality" (CPB 2004, 18).

Over the last decades our understanding of energy infrastructure reliability has undergone some profound changes. "Until about a decade ago, most infrastructures were run as public monopolies, dominated by an engineering culture, with an almost exclusive focus on the technical assets" (Weijnen and Bouwmans 2006, 127). This meant that "[a] ccident investigations remained largely limited to the discovery of the direct causes of accidents" (De Bruijne 2006, 52), i.e. the technical

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failures in pipelines, wires, pressure stations, generation plants, etc. caused by natural disasters, human errors, (lack of) maintenance work, and capacity overload. Latent causes of accidents were often neglected "if only because the far more subtle ways in which these factors caused accidents went largely unnoticed" (De Bruijne 2006, 52). Over the last decade however, the governance structure of energy infrastructures was dramatically altered because of liberalization, privatization, and unbundling. In the process, "the social network has become much more complex" as the number and variety of actors increased, their interests and responsibilities changed, and operational control was increasingly shared (Weijnen and Bouwmans 2006, 128). At the same time our understanding of infrastructures was altered. Insights about the interdependence and co-evolution of technology and institutions shaped our perspective of energy infrastructures as socio-technical systems (Nelson 1994; Murmann 2003; Perez 2001; von Tunzelmann 2003; Künneke and Finger 2006). In turn, our understanding of reliability changed. It became increasingly clear to researchers and experts that "accidents and reliability issues related to the operation of technologies, although perhaps directly caused by technical or human failures, often have deeper, less visible causes" (De Bruijne 2006, 52). Special attention turned to the impact of the organizational environment on technical failures. The occurrence of massive failures seemed to be largely dependent on adequate coordination among actors to prevent small mistakes from becoming big disasters; and the ability to communicate and coordinate in turn depended largely on the organizational structure within which energy producers, transmission and distribution companies, metering, regulators and consumers interact. Currently, researchers estimate that 80% of disasters in network industries are have human or organizational causes and only 20% are caused by design or other factors (De Bruijne 2006, 52). Contemporary disaster and safety management literature hence incorporates the perspective that organizational reliability is just as crucial to the safety of technical systems as the reliability of the equipment.

The realization that the reliability of energy infrastructures has organizational requirements has great implications for how we should think about planning for future energy systems. Not only do we need to consider which technologies to use and how to introduce them, but also how they should be operated to ensure infrastructure functioning once they are in place. These concerns may seem rather premature, but developing energy systems without planning for their functioning seems rather careless in return. Yet this is exactly what is happening. Consider in this regard the plans of governments for a transition towards more sustainable energy systems. While the technical development and market deployment of new renewable energy sources and carriers plus supporting technologies and infrastructures are thoroughly investigated in visions and roadmaps, the organizational requirements for their reliable functioning are often neglected. And if included, then organization is rarely linked to reliability concerns. Plans for solar panels, wind farms, or biogas rarely focus on how they may alter the interaction among producers, transmission and distribution operators, and retailers. This is also because technical solutions are often sought at the expense of exploring organizational possibilities. Unfortunately, it is not mere neglect that has caused our general disregard. There still exists a lack of understanding concerning the concrete relationship between the technologies and organization of infrastructures and its effect on overall system performance or reliability. Moreover, a "thorough understanding of how networks of organizations operate and coordinate their actions to reliably operate complex, large scale technological systems is lacking" (De Bruijne 2006, 72). So, what organizational structures may new renewable energy systems require; and how to know?

This PhD research picks up this challenge and investigates how to establish what organizational structures complement the technological characteristics of new sustainable energy infrastructures (in order to ensure their reliable operation)? It does so by first developing a 'framework for alignment' that may pinpoint the organizational requirements of new energy infrastructures and afterwards applying this framework on the case of a transition to hydrogen as a motor fuel in the Netherlands to illustrate its utilization and relevance. As we will see, answering this question serves many practical purposes beyond the immediate for reliability, such as aiding policy makers in overseeing the broader organizational implications of technical choices and assisting industry incumbent to sketch their role and responsibilities in future energy systems.

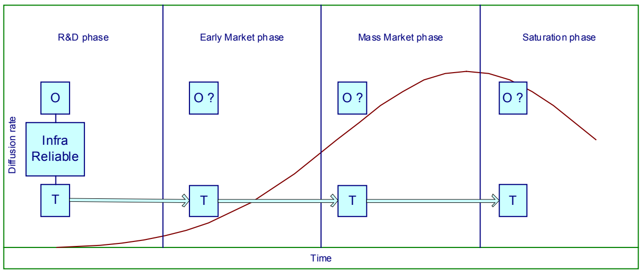

Figure 1. The neglect of organizational dimension of reliability in infrastructure planning

Bridging the Techno-Organizational Divide

Developing a framework for alignment starts by clearly identifying what is understood by infrastructure technologies and organizational structures. Technologies can be fairly straightforwardly be defined as all the technical assets or artifacts involved in the operation of an energy infrastructure. They are such tangible objects such as pipelines, wires, pressure stations, generation plants, control systems etc. Organization relates to the "context and forms of coordinative structures" among actors (De Bruijne 2006, 74). At its basic core, organizational structures are about the amount of actors involved in the operation of an infrastructure and the nature of their interaction (hierarchical/central or horizontal/decentral). [2] Typically, organizational structures are distinguished based on the degree of vertical integration involved (Williamson 1979, Harrigan 1984). A convenient categorization is provided by Provan and Kenis (2007). First is a form based on private contracting between all relevant actors (3 or more) in a decentralized way. Here, "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 central coordination is done by one participant / single lead organization or an entity external to the network. 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 one member has any significant leadership role.
The next matter to address is how to express technological characteristics in organizational requirements. Here I propose to take four subsequent steps. First, I start by addressing what technical functions are essential to system reliability for a given set of energy infrastructure

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

technologies. [3] A convenient starting point is given by Finger et al. in their 2006 article on the relationship between the degree of coherence between technologies and institutions in infrastructures and system performance. They distinguish between four technical functions that can be considered critical for safeguarding the technical complementarity and functioning of networks: interoperability, interconnection, capacity management and system management. 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). Examples are the complementarity between energy sources/carriers and delivery systems, like voltage levels and electricity wires, or energy characteristics and application requirements, like natural gas quality and domestic boilers. Interconnection deals with the "physical linkages of different networks that perform similar or complementary tasks" (Finger et al. 2006, 11-12). Typically, local gas distribution pipelines or electricity grids need to be linked to national and continental transmission networks. This also includes transmission planning, i.e. the design of "system additions to maintain reliability and to minimize cost" (Künneke and Finger 2007, 311). Capacity management concerns the allocation of "scarce network capacity to certain users or appliances" (Finger et al. 2006, 11-12). Issues pertain to the operational balancing (the continuous regulation of energy flows, checking content quality, and real-time disturbance response), unit commitment and capacity utilization (who should get network access when and where, the facilitation of actual access, and deciding starting up and shutting down generation), maintenance scheduling, and the long-term planning of network capacity, production facilities, and energy sources (Künneke and Finger 2007, 310-311). Finally, system management "pertains to the question of how the overall system (e.g. the flow between the various nodes and links) is being managed and how the quality of service is safeguarded" (Finger et al. 2006, 11-12). This mostly comes down to the continuous aligning of supply with demand, both in quantity (over and under production and consumption) and quality (grey or green energy), and ensuring that the energy system is able to adapt to changing conditions (McCarthy et al. 2007, 2157).

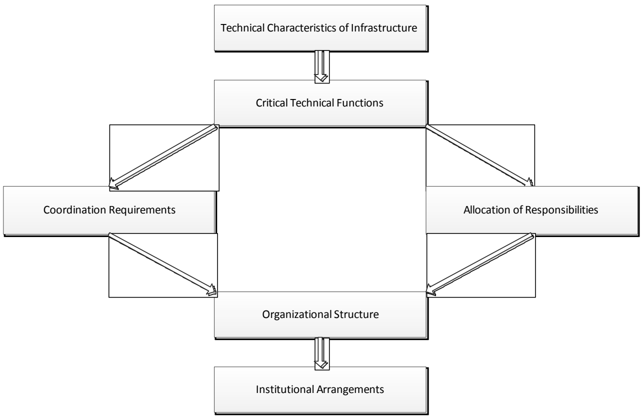

Figure 2: own illustration

After the critical technical functions have been identified, the next step is to allocate who is responsible for each one of them. The entities4[2] identified for the operation of infrastructure systems (or those that are related to or otherwise influence it) are the general steps in the supply chain: generation, trade, transmission, storage, distribution, metering, retail, and applications. The question to be answered is simple: which entity/entities is/are responsible for the facilitation of a certain critical technical function? For example, operational balancing is the responsibility of the operator(s). Interoperability may be the responsibility of all entities. To understand who is likely to be responsible for specific technical functions, the infrastructures of the current energy vectors are a helpful reference point. Hydrogen gas pipelines may transport hydrogen instead of natural gas, for example, but despite different pipeline material requirements might be operated very similar to natural gas from a coordination point of view. Once all critical technical functions have been mapped this way, an overall picture emerges that gives us some insights which entity(ies) are key and which relevant to a lesser extent. It also shows us the amount of entities involved per critical technical function.

The third step looks at the stringency of the coordination requirements of critical technical functions. Is central coordination required or may control be left to individual entities? Key in answering this question is the work of Künneke et al. (2008) on aligning institutions to technologies in network industries. It is here where the gap between the technical and social or organizational dimension of socio-technical systems is bridged. They start by classifying the control mechanisms required to facilitate critical technical functions into the scope of control (system, subsystem, or component) and the speed of adjustment (the time in which they must be executed: immediate, short term, medium term, long term) they involve. These categories of scope and speed in turn, so they argue, can be related to specific transactional characteristics such as asset specificity, frequency of transaction, and the uncertainty involved. By utilizing these insights from the field of New Institutional Economics, operational requirements of technical systems are translated into their coordination or organizational counterparts. In the end, twelve (3 scopes x 4 speeds) so-called 'modes of organization' are distinguished based on a central, top-down vs. decentral, bottom-up divide. Obviously, the larger the scope involved and the shorter the time to respond, the more stringent coordination requirements and necessity for central control. In other words, by classifying the critical technical functions' control mechanisms into their respective scope and speed, one can derive the degree of central coordination required.

Finally, the results of steps two and three need to be brought together in order to generate the overall organizational structure required. Whereas step 2 provides us with an idea of which entities are involved in the facilitation of a particular technical function, step 3 sheds light on the coordination requirements among the involved entities. Two questions remain however. First, which combination leads to what organizational structure? Second, how to combine the outcomes for each technical function into one whole? Regarding the former, and to avoid the immense complexity of all possible combinations, if we simplify the criticality of technical functions into high and low (central and decentral) and simplify the allocation of responsibilities into categories of whether there exists a clear entity that is most involved above others or whether multiple entities are roughly equally involved in the facilitation of a technical function, we may link the four resulting combinations to the

[3] *Technical functions are inherently different from 'mere' technical assets or technologies. While the functioning of assets is a purely technical issue, technical functions focus on how varying assets work together. As this requires human attention, they allow not only a focus on a few key variables, but also the move towards the organizational dimension.*

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

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

Regarding the second question, we should not simply throw all outcomes together; an eye needs to be kept on the organizational requirements of individual technical functions while the interrelation of entities in an energy system should not be forgotten. Some entities may need to work together for one technical function and not the other. To do justice to both, I propose to adhere to the following logic for putting the overall organizational structure together: those entities charged with the critical technical functions that require a centralized mode of organization should become the core entities in the overall infrastructure and those that deal with less critical technical functions may be vertically integrated with it, separated from it, or even be completely autonomous, depending on the degree of central coordination required. For example, the transmission operator is often the heart of an infrastructure because of the stringent needs posed by operational balancing, while the responsibilities of other entities are often defined in relation to it, though if technically possible they may operate independently from it. With this final step, the framework is finalized and we are ready to illustrate its utilization and practical usefulness.

Organizing a Hydrogen Fuel Infrastructure in the Netherlands

Throughout the last decade the Dutch government has repeatedly stated its intention to make a transition towards a more sustainable energy system (NMP4, 2000). Consequently, a plethora of new renewable energy technologies have been developing under its energy transition framework as well as under 'regular' energy policy. One possibility in particular, a transition to the use of hydrogen as a motor fuel as developed by the Energy research Centre of the Netherlands (ECN) for the European Union's (EU) HyWays project, presents an interesting and challenging case for framework exploration because it envisions the use of various hydrogen generation and transportation means, i.e. very different infrastructures, between 2010 and 2050.

In the early stage (2010-2030 / 2020), hydrogen is deemed available in three early user centers of Rotterdam, Amsterdam and the Arnhem-Nijmegen area. Hydrogen is generated from natural gas by small-scale onsite reforming at retail sites and delivered by tanker trucks (after liquefaction) to those urban fuel stations further away from natural gas pipelines or those fuel stations along the main highways connecting the centers. In Rotterdam, industrial hydrogen is also used to fill local fuel stations. The early user centers are independent in terms of network, though hydrogen vehicles should be able to refuel in any of them. In the medium term (2030-2045 / 2035), big changes are estimated to occur with the development of a regional hydrogen pipeline system (starting from Rotterdam) that connects most of the West of the Netherlands (the broader Rotterdam area, The Hague, Leiden, the larger Amsterdam area, and perhaps even Utrecht and Breda-Tilburg, while the Arnhem-Nijmegen user center is still independent from it. In terms of production, it is expected that large-scale central facilities replace onsite-production as the main means while coal and biomass join natural gas as potential sources. The proliferation of pipelines in and between cities and the necessity of large-scale hydrogen production to meet rising demand changes the role of onsite production and trucks delivery; whereas onsite production is likely to become only interesting in remote rural areas, hydrogen trucks may serve to both support the reach of onsite facilities in rural areas as well as extend the reach of pipelines and act as emergency capacity in case of demand and supply fluctuations in pipeline supplied areas. Finally, in the long term (about 2050 and beyond), a national pipeline network is expected to be in place that connects most of the Dutch cities in the West, South, and East. Only in the North may some onsite-production and truck distribution still be competitive / necessary. This national pipeline network now starts to become more complex however by the possibilities that interconnectivity offers to hydrogen producers wanting to reach markets. Hydrogen trade might be realizable from this point onward. Moreover, the use of renewable hydrogen sources also starts to become economical while the use of fossil fuels in large scale facilities diminishes or is subject to carbon capture and storage.

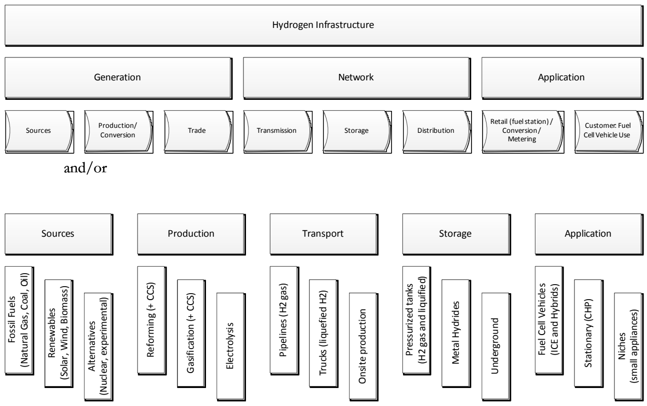

Figure 3. The hydrogen supply chain

With the technical roadmap presented, we are now ready to execute the framework's four steps on its three snapshots. So what are the organizational requirements of hydrogen systems in them? A quick look at the 2020 snapshot will help to exemplify its application. In 2020 the critical technical function of interoperability seems the most pressing matter. Standards regarding hydrogen use, production processes (gas purity), and truck delivery need to be in place and upheld. At the same time planning for future production processes and transportation technologies is required to enable the roll-out of the roadmap. Interconnection has similar concerns. While the early user centers are independent, the linkages between onsite production and natural gas pipelines and onsite production and truck distribution need to be facilitated. An eye also needs to be kept on the intended future interconnection of early user centers local networks via the pipeline system to be built. Capacity management seems to be a non-issue at this point in time. There is no need for operational balancing in onsite production and truck delivery. Of course, unit commitment and maintenance scheduling may still be required for truck delivery, but the failure of a truck only has a limited impact on the function of the overall network, unlike with pipelines for example. System management is also of little concern at this point because domestic natural gas supplies and little consumption it should be rather simple to match supply and demand. On the other hand, some consideration should go to facilitating a co-development of demand and supply.

Regarding the allocation of responsibilities, onsite producers and truck distributors (where active) are involved in the daily operation of the infrastructure and responsible for all technical functions, except perhaps capacity management due to the lack of necessity for it. Regulators and retailers (fuel stations) play a secondary role because they do not actively operate the infrastructure, but are involved in setting standards, future planning, or otherwise influence operation. For example, retailers play a role in measuring demand and the planning for future fuel station locations while regulators may try to promote delivery of hydrogen to specific areas and check general compliance to standards. Their involvement in facilitating interconnectivity or capacity management is unlikely however.

Regarding the coordination required, compliance to standards (interoperability) and facilitation of linkages (interconnectivity) takes place on the short term and within the entities (component level) and user center (subsystem level) respectively. The immediate term is not required due to the nature of truck delivery in contrast to the more stringent needs of a pipeline system. Regulatory checks of the compliance by entities however are system wide and need to be done on the short term as well. Interoperability is of primary importance at this early stage to ensure that all the various hydrogen technologies are operating complementary so that hydrogen vehicles are able to refuel at any fuel station in all of the user centers. The planning for future developments in contrast is a system wide long term issue for both. Capacity management can be largely ignored and where not involves no coordination; all possible tasks take place within the onsite or truck distribution entity (component level) and on the short term. System management is not much of an operational challenge considering the possibilities that natural gas offers for increasing or decreasing hydrogen production. Nevertheless, some medium-term monitoring and coordination to ensure mutual adjustment among the entities within a user center (subsystem level) might be useful to prevent major mismatches in demand and supply. Summing up, most issues are a matter of either monitoring and corrective action on the component level for daily operations or system wide coordination for long term planning. Both combinations of scope and speed do not necessitate central operation. Only interoperability, where standards need to be ensured across all user centers hints at the need for central coordination under a regulator. But that is corrective in nature; individual onsite facilities and truck companies remain responsible for operations.

Finally, putting steps two and three together we may arrive at an overall organizational structure that seems caught somewhere between incidental interaction and common operation. On the one hand, the daily operation of the technical functions seems to involve the efforts of individual entities and do not require coordination as such. On the other hand, setting the standards for daily operations and planning for future developments seems to benefit from regular interaction. In other words, if 2020 would be the end-state for the hydrogen infrastructure, spontaneous coordination may well be sufficient. In that case it can be left to individual entities that occasionally interact to settle incidental contracts. However, since we know that the roadmap intends the interconnection of the early user centers, the switch to pipelines as the main network means, and large-scale production as a necessity to meet future demand, the coordination needs for the planning for this scenario do tend to tip the balance in favour of a form of common operation since it implies regular interactions to operate the hydrogen infrastructure.

Implications

The framework of alignment as presented and applied above seems to have established the means to express the technological characteristics of renewable energy infrastructures in terms of their organizational requirements in light of ensuring reliability. This does not imply however that there is no room for improvement. In my PhD research there was considerable testing of the framework on existing energy infrastructures and comparison between the results and actual organizational structure. This led to the identification of a number of features of energy systems that deserved consideration. Matters such as network complexity, intensity of use, benefits of experience and routines, and the stable or rapidly changing nature of networks in which the infrastructure operates and/or expands all needed to be considered. Though they are not technical functions as such, these features affect the parameters of the functions and help shape the necessity and possibility for coordination. Consequently, they were incorporated into the framework, but their exact influence remains open to debate. Moreover, the framework in general seems to be attuned to a more mechanical operation of infrastructures; it remains to be seen how it will manage to incorporate the information management that for example smart grids seem to require. How to incorporate that into the overall organizational structure? Nevertheless, the current framework seems to provide a useful starting point.

While the application of the framework manages to arrive at a complementary organizational structure of a hydrogen network anno 2020, the full potential of utilizing the framework only becomes obvious when the other snapshots are added. Without repeating the steps here, but having done them in the research, let me state that the suitable organizational structures in 2035 and 2050 are ‘hierarchical organization’ and ‘lead entity’ respectively. Combined they serve to create an organizational roadmap that complements the technical. This has some interesting implications. First, we can see that the reliable operation of new energy systems may have varying organizational requirements at various stages of development. The question becomes whether these organizational changes can be met. Introducing new technologies might prove to be considerably easier than changing sector organization, i.e. they way in which entities interact to coordinate for reliability. The lengthy and troublesome liberalization and privatization process are a case in point.

The notion of organizational lock-in and path-dependency should therefore be included into planning roadmaps towards future energy systems. Moreover, in how far do techno-economic and organizational logic conflict? The HyWays roadmap was based on a desirable techno-economic picture, but are different hydrogen options or development paths now preferable? Second, because the framework helps to set up an organizational roadmap, it can be used as a tool by policy makers to assess the organizational requirements and broader implications of technical changes in energy infrastructures while sector incumbents may reflect on their changing role and responsibilities (towards reliability) over time. This helps them make investment decisions.

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