Challenges for the regulation of critical technical functions in infrastructures: The case of electricity

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Abstract

This paper deals with the interrelation between the technological features of the electricity sector and the evolving institutional arrangements of a liberalized market. Certain critical technical functions need to be supported by suitable institutional arrangements in order to safeguard a satisfactory technical functioning of this infrastructure. It is argued that there is a necessity to align technological and institutional regimes into a coherent framework in order to develop a sustainable sectorial organization. This paper illustrates that the regulation of this important sector needs to take technology explicitly into consideration, either as an enabling or restricting factor. Two different regulatory approaches are addressed.

1 Introduction

The electricity sector is subject to a process of fundamental restructuring, often indicated as liberalization, privatization and/ or deregulation. This process, which started some two or three decades ago, had a major impact on the structure and the performance of this sector on a global scale. Electricity developed from a utility to a commodity; from a national oriented industry into a global business; from dominant political involvement to a market driven activity. Traditionally the electricity sector was perceived as a natural monopoly. Accordingly electric utilities were granted a regional regulated monopoly in order allow the realization of low costs, while safeguarding certain public interests. Under these conditions integrated firms provided all major services, i.e. generation of electricity, transport, distribution and delivery to the final customer. However, it became apparent that certain parts of the industry, especially generation and trade, could be exposed to competition, which potentially increases the economic performance[1]. But there were also political reasons for liberalization. The European Union for instance, promoted the restructuring of the electricity market as an instrument to further integrate the national markets of the member states into a single European market.[2] Well-known examples for the liberalization of the electricity sector which often serve as good or bad examples include the Scandinavian countries, the United Kingdom and in the USA: PJM & California.

Up to now, the results of this restructuring are somewhat mixed. In some cases liberalization worked well in terms of significant lower prices, higher productivity and more services to the customer[3]. In a recent report on EU price developments it was demonstrated that after liberalization in the past 10 years the prices dropped on average 15% in real terms.[4] But there

[1] The seminal work of Joskow & Schmalensee 1983 was very important in this respect.
[2] Midttun 1997
[3] Amundsen 2006
[4] Kema 2005

is also increasing concern with respect to the safeguarding of the reliability of electricity supply. A key event in this respect was the California energy crisis in 2000 and 2001. Major blackouts affected millions of customers. At several occasions there was insufficient generation and/ or transport capacity to meet demand. This seriously disrupted economic activities not only locally, but even on a global scale. It empirically proved that California was not a stand-alone case. Especially in 2003 several significant incidents occurred. Examples include:

- 14-8-2003: North American blackout
- 23-9-2003: Blackout in Denmark and Sweden
- 27/28-9-2003: Blackout in Italy
- 28-9-2003: London blackout

These and other incidents contributed to the growing public concern about the reliability of the electricity system under liberalized market conditions. Against this background the paper deals with the question whether there is a certain interrelation between the technological features of this sector and the newly evolving institutional arrangements. As a starting point of the analysis, we assume that critical technical functions of the electricity sector need to be supported by suitable institutional arrangements in order to safeguard a satisfactory functioning of this infrastructure. This results in the following problem statement:

What are critical technical control mechanisms in the electricity system and how are they related to institutional arrangements that support the technical functioning of the system?

To emphasise, this paper only focuses on one single aspect of the performance of the electricity sector, i.e. the technical performance. There are of course other important aspects of the performance that are not addressed here, including the economic performance (efficiency, pricing, investment, risk) and the socio-political performance (public services, environmental objectives, national interests). Our argument is however, that a reliable technical performance serves as a prerequisite to be able to realize the above-mentioned economic and socio-political objectives. This paper aims to elaborate on the relationship between critical technical functions and the supporting institutional arrangements. Our hypothesis is that there needs to be some coherence between technology and institutions, in order to allow for a satisfactory technical functioning of this sector. This results in some challenges for the regulation of the electricity sector.

This paper is structured as follows. Chapter 2 provides a short description of some relevant characteristics of the electricity sector. Consequently, the critical technical functions can be identified in chapter 3. Chapter 4 deals with the critical institutional arrangements that support these technical functions. Chapter 5 relates the critical technical functions to the critical institutional arrangements. The nature of the possible interrelationship between technology and institutions will be exemplified. We elaborate some challenges for the regulation of the electricity sector. Chapter 6 summarizes the main findings and conclusions.

2 Description of the electricity sector

From an economic perspective the electricity system can be described by a value chain that is depicted in figure 1. Successive operational functions are aligned from production to the final delivery to the customer.

Figure 1: The electricity value chain under liberalized market conditions

Legend: Light blue: market-based commercial functions

Dark blue: regulated monopolistic functions

The production of electricity entails the generation of electric power by means of different primary energy sources, like for instance natural gas, coal, oil, or uranium. Traditionally the generation of electricity is a specialized production process in large-scale plants. The generated electricity is traded on wholesale markets, which includes bilateral contracting as well as spot market arrangements. Transmission and distribution denotes the physical transport of electric power though dedicated high voltages lines that are ultimately transformed into low voltage power to be served to the final customers. These network-related activities are typically organized as regulated functions of a natural monopoly. At the customer side of the value chain the electricity is metered, sometimes by specialized firms, and sold through retailers. In order to allow for competition, liberalization of the electricity market requires a decomposition of the value chain that results in the unbundling of monopolistic network related services (i.e., transmission and distribution) and competitive commercial functions (including production, trade, metering and supply). This unbundling is necessary to prevent for unwarranted strategic behavior vis-à-vis the regulated parts of the market and hence abuse of monopolistic power. Unbundling can be institutionalized in different ways, i.e. by the separation of the administration or management, legal or ownership unbundling.[5] Prior to liberalization the value chain was typically integrated into the boundaries of single regulated utilities, in the most extreme case from production to sales. We will reflect on the consequences of the unbundling of the value chain later in this paper.

3 Critical technical functions

Criticality can be related to the conditions under which a complex system fails to meet the expected performance.[6] We will elaborate this notion for the case of the electricity sector, which has some peculiar technical characteristics. Since electricity cannot be stored on a significant scale, the generation of electric power needs to be balanced with demand

[5] See for instance: Künneke & Fens, forthcoming
[6] http://en.wikipedia.org/wiki/Criticality_matrix

continuously and nearly instantaneously. With an increasing size of the system with millions of customers and a large amount of different production sites, this becomes a very challenging technical task. As a further complicating factor, the flow of electricity through the network cannot be actively controlled. Following the law of Kirchhoff, electric power is directed through the transmission and distribution networks by the least electric resistance. This makes that the components of the electricity system are physically highly interrelated with a high degree of complementarity. For example, the generation of electric power depends on the availability of sufficient transmission and distribution capacity throughout the entire network, in order to be delivered to final customers. However, since the path of physical delivery cannot be controlled, the network functions like a common resource, for which the physical input and output have to be in equilibrium in order to maintain the system. A disturbance of this technical equilibrium can for instance be triggered by a sudden interruption of an important transmission line, which causes a cascading failure of the neighbouring networks resulting in the interruption of the delivery of electric power for a considerable part of the system (i.e. a blackout).

Reliability is thus an important issue in the electricity sector. Reliability denotes the ability of the electricity system to 'perform/maintain its functions in routine and also in different hostile or/and unexpected circumstances'.[7] Taking this definition as a point of reference, reliability can be related to various technical features of the electricity infrastructure. Examples include the reserve margin between installed capacity and expected demand, the configuration of the network, the network topology, etc. In this paper we only focus on critical technical control functions that support the integrity of the electricity system[8]. We consider the following functions.[9]

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[7] http://en.wikipedia.org/wiki/Reliability
[8] With respect to other network industries a similar approach is chosen by Nightingale 2003
[9] Finger et al. 2006, Hirst 1997

Capacity management is an important control function because the components of the electricity system are scarce resources with limited physical capabilities. Capacity management deals with the allocation of these scarce resources at three different levels.[10]

- Operational real time capacity management encompasses the continuous technical balancing of the electricity system. This includes automated protection of system elements in case of malfunctioning[11], certain routines for disturbance response like the adjustment of generation and breakers, and regulation and voltage control.
- Tactical capacity management deals with the allocation of existing resources in order to meet the expected demand. Electricity suppliers have to secure sufficient production capacity in order to meet the contracted demand. Typically they commit generation capacity to the system operator, usually 24 hours in advance for a period of 30 minutes. But also longer time periods, for instance a week ahead, are possible. The system operator is than able to calculate whether the committed capacity is sufficient to meet the expected demand, and whether the system is physically able to support the intended transactions. Another typical aspect of tactical capacity planning is maintenance scheduling. Generation plants need periodical check-ups and repair in order to secure their proper functioning. Especially for larger plants, these outage times are significant and they influence the availability of the production capacity, which might have negative consequences for the system's reliability.
- Strategic long-term capacity management addresses the planning of the newly to build long-living components like for instance the generation plants. Another aspect of long-term planning is the choice for certain generation technologies (like nuclear, fossil, or renewable), and securing the availability of important inputs like primary energy. The reliability of the electricity system can be increased by a certain diversity of technologies that rely on different primary energy sources. Also the planning of new network capacity fits into this category.

[10] Ten Heuvelhof et. al. 2003
[11] The most straightforward example of automated protection is the safety fuse.

Interconnection deals with the physical linkages of different networks that perform similar or complementary tasks[12]. As such, interconnection is closely related to the technical system's boundaries. Electricity transmission networks are often operated on a national or state level and are interconnected with each other across national boundaries. Through interconnection reliability is enhanced, because in a case of emergency supplementary resources are available from other systems. If for example a large-scale power plant is unexpectedly not available, backup capacity can be more easily acquired in a larger interconnected system than in a small stand-alone situation[13]. On this international scale there are various organizations that technically enable and support the international exchange of electric power. In Europe for instance, the UCTE (Union for the Co-ordination of Transmission of Electricity) is such an organization of some 22 member states. There are also some limited opportunities for dedicated merchant lines that can be operated independently from the public network. This requires specific technical and economic conditions that are only rarely meet. [14]

Interoperability is realized if mutual interactions between network elements are enabled in order to facilitate systems' complementarity. Interoperability ensures that the elements of the network are combinable.[15] In other words, interoperability defines the technical and institutional conditions under which the electricity networks can be utilized. Examples are technical norms & standards and regulatory conditions for access. For example, the generated electric power needs to fulfill specific technical requirements with respect to the voltage level in order to support the functioning of the network. In this sense, interoperability is also of

[12] Economides 1996
[13] Of course interconnection is also important for an economic perspective to facilitate international trade.
[14] Typically the cables are operated independently form the public network. This is necessary to be able to capture sufficient economic rents and to avoid unwarranted externalities caused by loop flows. Technically these are direct current cables. Examples include the NorNed cable between Norway and The Netherlands, and the BritNed cable between the UK and The Netherlands.
[15] Sometimes the notion of system compatibility is also used in this context. See for example Economides 1996.

strategic importance. It determines the conditions of use as well as the rules for entry and exit to this specific facility.

Figure 2 summarizes these critical technical functions. For the further analyses we take two aspects into consideration to operationalize different aspects of criticality.

- The time period in which these functions have to be performed. The shorter the time period in which certain functions have to be performed, the more critical they are. Figure 2 illustrates that the operational real-time capacity management is the most critical in this respect. Automated protection and disturbance response need to be performed almost instantaneously. On the contrary, interoperability is far less critical in this respect because this can be accomplished within year or decades.
- The technical scope of these functions. The greater the technical scope, the more critical the technical function. Al aspects of capacity management are related to the technical boundaries of a given electricity infrastructure. Typically these are defined by the technical control boundaries of the high voltage transmission network. In many countries national or state borders delineate this control area. Al functions of capacity management are equally critical in this respect. For example, if there is no sufficient generation capacity, the reliability of the entire system will suffer. The same holds if there is a poor disturbance response. In general, these functions cannot be a priori restricted to certain parts of the network, which could potentially decrease the criticality.

  Interconnection and interoperability deal with the external relations to other electricity systems. Generally, modern electricity systems are highly interconnected and thus strongly depend on each other. For example, part of the problem in California energy crisis was a lack of sufficient transmission capacity to import electric power from neighboring states. In the EU for instance, wind power production in the northern part of Germany impacts the performance of the Dutch grid. The above-mentioned North American blackout in 2003 crossed several state boundaries and electricity systems. These examples illustrate that apparently there are insufficient technological means to isolate the performance of single electricity systems from possible disturbance of neighboring systems. Hence, interconnection and interoperability are potentially to the same degree critical as capacity management.

Table 2: Time periods of control for critical technical functions in the electricity sector[16]

Critical technical function	Description	Time scale	Technical scope
Operational real-time capacity management			System
Automatic protection	Minimize damage to equipment and service interruptions caused by faults and equipment failures	Instantaneous	
Disturbance response	Adjust generation, breakers, and other transmission equipment to restore system to scheduled frequency and generation/ load balance as quickly and safely as possible.	Instantaneous to minutes to hours	
Regulation and voltage control	Adjust generation to match scheduled intertie flows and actual system load. Adjust generation and transmission	Seconds to minutes	
Tactical capacity management			
Unit commitment	Decide when to start up and shut down generating units, respecting unit ramp-up and -down rates and minimum runtimes and loadings	Hour ahead to week ahead	
Maintenance scheduling	Schedule and coordinate interutility sales and planned generating-unit and transmission-equipment maintenance to maintain reliability and to minimize cost	1 to 3 years	
Strategic long-term capacity management			
Generation planning	Develop a least-cost mix of new generating units, retirements, life extensions, and repowering based on long-term load forecasts	Several years	
Fuel planning	Develop least-cost fuel supplies, contracts, and delivery schedules	1 to 5 years	
Interconnection			System
Transmission planning	Design system additions to maintain reliability and to minimize cost	Several years	
Interoperability			
Norms and standards	Develop norms and standards that enable a reliable functioning of the system and allow the interconnection to other (international) networks.	Several years to decades	

4 Critical institutional arrangements

Critical institutional arrangements are those that are related to the above-mentioned critical technical functions. These institutional arrangements are crucial to support the satisfactory

[16] This overview is based on Hirst, 1997, p.6

technical functioning of the electricity infrastructure. Figure 3 provides an overview of typical institutional arrangements that support the above-mentioned critical technical functions of electricity systems. Like in the previous section we relate to the time scale and the scope as important aspects to describe the degree of criticality. With respect to the institutional arrangements, the time scale is taken as given, because it is predetermined by the technical necessities of the electricity system. For instance, operational real-time capacity management needs to be performed in the given short time periods, otherwise the system will technically fail.

The typical institutional arrangements as denoted in figure 3 are related to liberalized electricity markets. [17] The institutional scope is determined by the decision rights and/ or property rights that are assigned to the institutions. In the following, these typical institutional arrangements will be shortly characterized.

[17] It has to be acknowledged that there are significant differences with respect to various national approaches to the restructuring of the electricity market. However, the argument of this paper deals with some general institutional features that are common to most liberalized electricity markets.

Figure 3: Critical institutional arrangements in the electricity sector

Critical technical function	**Time scale**	**Institutional scope**	**Typical institutional arrangements**
Operational real-time capacity management			
Automatic protection	Instantaneous	Transmission system	Independent system operator (ISO): - Conduct regulation - monopolistic - private or public entity
Disturbance response	Instantaneous to minutes to hours		
Regulation and voltage control	Seconds to minutes		
Tactical capacity management			
Unit commitment	Hour ahead to weeks ahead	Market (Subject to technical system restrictions)	Market monitored by the ISO: - bilateral contracts - power pools - monitoring arrangements by the ISO - structural regulation - private (or public) ownership
Maintenance scheduling	1 to 3 years	Firm (subject to market functioning)	- Intra firm arrangements, sometimes monitored by the ISO
Strategic long-term capacity management			
Generation planning	Several years	Firm	Intra firm arrangements
Fuel planning	1 to 5 years		
Interconnection			
Transmission planning	Several years	Transmission system	- Transmission system operator (TSO), subject to conduct regulation by an independent regulator.
Interoperability			
Norms and standards	Several years to decades	Transmission system	(Self-) regulation of TSO's or regulatory office

The institution of an Independent System Operator (ISO) takes care of the various technical functions of real time capacity management. The decision rights are typically related to the high-voltage transmission network. Because of the monopolistic nature of this function, a regulatory framework is needed to safeguard independent and non-discriminatory behaviour of the ISO. This is a case of conduct regulation. The ownership rights associated to the ISO can be either public or private.

Tactical capacity management is institutionalized by various market-based arrangements. However, the market outcome is monitored and coordinated by the ISO in order to secure the technical feasibility. The regulatory framework includes the stimulation of a competitive market structure and predominantly private property rights.[18] Unit commitment can be realized by various institutional arrangements that are based on bilateral contracts or so-called power pools. Bilateral contracts specify the commitments of producers/ suppliers to provide a certain amount of electricity for a certain period of time to final customers in exchange for some financial rewards. Typically the greatest part of the electricity flows is allocated in this way. Power pools are market places to exchange electricity anonymous 'on the spot' or for some weeks ahead. Exchanges on the power pool are often residues from long-term bilateral contracts, i.e. surpluses or shortages to balance expected demand and supply. It is required that for each day ahead, market participants have to announce 24 hours in advance for a period of 30 minutes their contractual commitments to produce or deliver electricity[19]. The ISO monitors whether these commitments can be technically realized such that production and supply are in equilibrium, and provides coordination if this is not the case. Besides, the ISO monitors the actual fulfilment of these commitments by the market parties since demand and supply are not completely predictable due to unforeseen outages or short-term changing consumption patterns. As a consequence the ISO needs to safeguard back-up capacity and organize the reconciliation according to the actual production and consumption patterns.

Decision rights with respect to maintenance scheduling might be completely assigned electricity producers. In this case they are expected to align maintenance with their contractual arrangements. However, there are opportunities for strategic behaviour and thus influencing market outcomes. For instance, assigning a power plant for maintenance in a scarce market can drive the prices up significantly and threaten the technical reliability of the

[18] There are however examples of liberalized electricity markets with public ownership rights, including the Scandinavian countries or The Netherlands.
[19] This is required for the so-called program responsible parties; including generators and trades.

system. This has been the case in the California energy crisis.[20] In order to prevent this unwarranted behaviour, the ISO can be assigned to monitor and coordinate maintenance plans of the electricity generators.

The institutional scope of the tactical capacity management is basically determined by the market for electricity (unit commitment) or even the boundaries of individual firms (maintenance scheduling). The ISO has an important role to align the market outcomes with the technical feasibilities of the electricity infrastructure and to prevent unwarranted strategic behaviour.

Strategic long-term capacity management is taken care off at the firm level by the electricity generators. According to their individual objectives, firms determine whether they want to invest in new capacity or phase out existing plants, and their preferences for certain primary fuels. This is generally left to market incentives without further regulatory coordination.

The function of interconnection is assigned to the Transmission System Operator (TSO), which has the ownership and decision rights with respect to the transmission network. Because of its natural monopolistic position, this TSO is subject to sector specific regulation, implemented by an independent regulatory office. There are specific rules and criteria under which investments in the transmission network are considered essential and thus supported by the regulatory office. The tariffs are sanctioned by the independent regulator, considering economic efficiency criteria. As mentioned earlier, there are some limited opportunities for third party investments in the transmission network by means of merchant lines. In some countries, ISO and TSO are merged in one single organization.

[20] De Vries 2004

The interoperability of different transmission networks is institutionalized by self-regulation, or in the case of different national transmission systems, by a federal regulatory office. The institutional scope is determined by the transmission network.

Prior to the restructuring of the electricity market, the institutional arrangements were quite different, as mentioned in chapter 2. Basically, integrated firms owned and operated all vital components of the value chain. Most of the above-mentioned institutional arrangements were internalized in the firm, and consequently the institutional boundaries of the firm were identical with the technical boundaries of the electricity system. The consequences of this change of institutional arrangements with respect to the safeguarding of the technical functioning of this sector are addressed in the next chapter.

5 Challenges for the regulation of critical technical functions

Table 4 compares the critical technical and institutional arrangements in the electricity sector. Since the time scale is assumed to be identical in both cases, the comparison is focussed on the technological and institutional scope. This results in some challenges with respect to the regulation of this sector.

Figure 4: Comparison of the critical technical functions and critical institutional arrangements

Critical technical function	**Time scale**	**Technological scope**	**Institutional scope**	**Typical institutional arrangements**
Operational real-time capacity management				
Automatic protection	Instantaneous	System	Transmission system	Independent system operator (ISO): - Conduct regulation - monopolistic - private or public entity
Disturbance response	Instantaneous to minutes to hours			
Regulation and voltage control	Seconds to minutes			
Tactical capacity management				
Unit commitment	Hour ahead to week ahead	System	Market (Subject to technical system restrictions)	Market monitored by the ISO: - bilateral contracts - power pools - monitoring arrangements by the ISO - structural regulation - private (or public) ownership
Maintenance scheduling	1 to 3 years		Firm (subject to market functioning)	- Intra firm arrangements, sometimes monitored by the ISO
Strategic long-term capacity management				
Generation planning	Several years	System	Firm	Intra firm arrangements
Fuel planning	1 to 5 years			
Interconnection				
Transmission planning	Several years	System	Transmission system	- Transmission system operator (TSO), subject to conduct regulation by an independent regulator.
Interoperability				
Norms and standards	Several years to decades	System	Transmission system	(Self-) regulation of TSO's or regulatory office

Comparing the institutional and technological scope of the critical technical functions clearly illustrates quite some interesting discrepancies. From a technical perspective, all critical technical functions need to be resolved on a systems level. On the other hand, the critical institutional arrangements relate to quite some different scope of decision rights or ownership rights. First we will compare more in detail the different institutional and technological scopes. Second, we elaborate on the possible challenges of these differences with respect to the regulation of critical technical functions in the electricity sector.

5.1 Comparing technological and institutional scope

From a technological perspective, the system can be delineated by at least two criteria. First, the opportunities to actively influence important technical system parameters and hence actively influence the performance. Second, the degree of technical interdependence of the various nodes and links. Through this interdependence the technical performance of the system is influenced, without necessarily an opportunity for technical intervention. Taking the first criterion as a point of departure, the technical scope of electricity systems is often defined by the boundaries of control of the national or state transmission system, including its underlying distribution networks. The second criterion would include not only these national or state systems, but also all interconnected systems as well. The stronger the degree of interconnection, the more the technical scope of control needs to be expanded beyond the single state or national networks in order to prevent unwarranted negative technical effects, like for instance cascading blackouts or uncontrolled loop flows. For large integrated systems like in the USA and the EU there is an increasing technical need for these supra national technical control mechanisms.[21]

The critical institutional arrangements relate to different levels of scope of control with respect to the decision rights and ownership rights: transmission system, market and firm. The transmission system is associated to the high voltage network, i.e. the technical backbone of

[21] The blackouts that are mentioned in the introduction might have been prevented if such overarching technical control would have been in place. In the EU and the USA there is a tendency towards more technical coordination between different transmission systems. However, this is still in an infant stage and there are significant political obstacles to be resolved.

the national or state system, however not necessarily including the distribution networks. This does not impose significant technical problems of control, as long as the major production facilities and big industrial consumers are directly connected to the transmission lines. In this case the function of distribution networks is restricted to the delivery of energy. However, technical problems do arise, if there is a significant contribution of decentral small-scale power production that is connected to the low voltage distribution network. In this case some of the critical technical functions (i.e. real time capacity management) need to be performed on this network level. However, distribution networks are technically not equipped to this task. The ISO, which operates on the high voltage level, is often not able to monitor or control the activities of these small generators, which potentially contributes to the instability of the system.

The ‘market for electricity’ is a quite vague notion that cannot clearly be delineated against the technical system boundaries. The market might be local or regional within a given transmission system, but it can also easily cross these boundaries though trade arrangements on an international or global level. The boundaries of these markets are not necessarily identical with the technical system boundaries. In the market coordination is trusted to the well-known ‘invisible hand’ that depends on the price incentives provided to individual actors seeking to satisfy their own objectives. This ‘co-ordination by coincidence’ is quite different from the needs for technical planning to secure reliability on the system level.

Finally we need also to consider the institutional scope of the firm. Under the conditions of a liberalized market, firms are independent actors competing against each other’s. They will be driven by their own interest, within the institutional boundaries of the firm. They are part of the technical system, but they are expected only to serve the technical needs of the system if this contributes to the firm’s objectives.

5.2 The need for coherence between technology and institutions

Regulation is perceived as a way of framing property rights and decision rights in order to influence (limiting, orienting, or supporting) decisions, i.e. in the case of this paper decisions with respect to the technical reliability of the electricity system. The stronger the institutional arrangements are oriented towards the market mechanism and private actor decision-making, the more decreasing the opportunities of framing decision rights and property rights. [22] In this case the individual objectives and preferences can be more easily prevailing against the technical needs for safeguarding the reliability of the electricity system. In the following we will elaborate this proposition more in detail.

It is a significant challenge of the liberalized electricity market to align the mode of governance with the needs of the critical technical functions. There needs to be a certain degree of coherence between institutions and technology in order to support the functioning of the system.[23] From an economic perspective this coherence needs to be realized with a minimum of transaction and production costs. This notion of 'coherence' is quite vague and needs to be further operationalized. In the following we propose some interrelated criteria and exemplify them for some cases that are specified in table 4.

Comparable time to react to signals of critical technical functions. As pointed out in the previous chapters, there are quite some ridged technical time restrictions for resolving problems with respect to certain critical technical functions. Institutional arrangements need to obey to these restrictions, especially for instantaneous or short-term needs of critical technical functions.[24] However, there might be discrepancies with respect to mid-term or long-term decisions.

[22] Groenewegen, Künneke and Menard 2006
[23] Finger, Groenewegen and Künneke 2005
[24] Joskow, 2003, p.551

Comparable technological and institutional scope. As pointed out in the previous section, there are important differences between the technical scope of an interconnected electricity system, and the institutional scope of the ISO, TSO, market or single firm.

Compatibility of information flows. The criticality of technical functions needs to be signalled in as soon as possible to the agents that own the decision rights and the technical capabilities to intervene into the system. Technical and economic information flows need to be parallel to each other with the same directionality, to be received by the technically and economically most competent actor to stabilize the state of the electricity system.

Comparable incentives. A technical need to intervene into some critical functions should be directly related to a comparable economic incentive. For instance, generation planning needs to be coordinated on a systems level in order to prevent for unwarranted shortages and system bottlenecks. As mentioned in the introduction, there is an increasing concern that the liberalized electricity market might fall short in this respect. In present electricity systems the free market does not provide sufficient incentives to invest in capacity that only might be used under very rare conditions.

Comparable economic and technical agents. Under the most ideal circumstances, the technical control of critical functions should be aligned with the decision rights and property rights of the economic agents. In this case the actor is exposed to the technical and economic incentives that signal a possible need for intervention and he is able to do so. The position of electricity consumers provides an interesting case in this respect. Traditionally power engineers treat electricity consumption as an external parameter that cannot be directly influenced.[25] However, nowadays consumers could technically contribute to the stability of the system, by reducing their demand as means of disturbance response. An intelligent meter would be needed to provide suitable economic incentives to the final customers, for instance

[25] For this reason it is considered a ‘disturbance’ within the electricity system.

by higher prices. However, final customers are only treated as economic actors (providing revenues), while neglecting their possible technical contribution to the technical reliability of the system. There are also other, less futuristic examples. The Independent System Operator (ISO) has only limited decision rights with respect to operational and tactical capacity management, while he is legally obliged not to take economic interests. Market parties, like for instance electricity producers, predominantly act according to their economic interests, while neglecting the technical needs for safeguarding the critical technical functions.

Comparable performance criteria. The technical and economic performance needs to be related to comparable criteria in order to provide suitable incentives to safeguard the reliability of the system. For instance, maintenance scheduling is a critical technical function that requires a certain planning in order to guaranty system reliability. Firms might not be interested in the reliability of the system, as long as they are able to use maintenance as a strategic parameter to realize competitive advantages or manipulate the market price. In this case, the economic performance criterion of profitability is not coherent with the technical need to safeguard the system's reliability.

Comparable technical and economic preferences. From the perspective of technical system control there is a strong preference to meet the needs of the critical technical functions. The bottom line is of course that the electricity system has to function in a technical sense, otherwise no economic activities are possible. Given these basics, economic actors might not necessarily consider it in their own interest to contribute to the technical system reliability. They might be satisfied with a lower degree of reliability, or have different interests with respect to the necessary investments. Because the electricity network has economic features of a public good, the free rider problem arises. Actors just might wait for others to take action. Besides, there are positive externalities, which mean that the benefits of individual investments are spread throughout the system. Obviously this influences the willingness to invest. This is the classical economic problem of common pool systems.

5.3 Challenges for the regulation of liberalized electricity markets

The previous section illustrates that there is considerable incoherence between the governance of critical technical functions and critical institutions. This jeopardizes the technical system reliability and does not contribute to economic efficiency. This incoherence appears to be a fundamental problem of liberalized electricity. What are the opportunities to resolve this problem from a regulatory perspective?

Taking the technological characteristics of the electricity system as a given, it seems that the vertical unbundling of the value chain causes problems with respect to the institutional scope. By separating the monopolistic network related activities from the competitive parts of this sector (generation and trade), there is no longer an obvious economic interest for safeguarding the critical technical functions of the system. The institutional unbundling of the electricity market is challenged by the technical interdependency and complementarity of the electricity system. The traditional sector organization of vertically integrated regional monopolies fitted very well to these technical requirements. The institutional boundaries of the firm were identical to the boundaries of the local market, which were identical to the boundaries of the local technical system. Under the conditions of a liberalized market, the question arises whether there are appropriate regulatory instruments to create a suitable institutional framework that re-aligns the critical institutional arrangements with the critical technical functions. The previous paragraph provided some examples of the very fundamental nature of the incoherence between institutions and technology. If this can be proven in further research, it appears that the present institutional structure of liberalized electricity markets is not sustainable. Institutions need to be rearranged in order to allow a vertical re-integration of the value chain. This does not necessarily mean a return to the natural monopolies of the past. A further economic consolidation and thus concentration of the market might also solve some of the problems signalled in this paper. In many parts of the world, including the EU and the USA, such a consolidation process already started some years ago. Within the EU it is expected that ultimately some five firms might dominate the internal electricity market. These large-scale dominant firms have a much stronger economic interest in safeguarding the critical technical functions. The institutional scope is closer to the technical system scope; therefore the technical and economic preferences are more aligned. Hence, there are fewer opportunities for free riding, and more chances to capture the benefits associated with positive externalities. Under these conditions, regulation should be reoriented towards the support of the technical functioning of the system, rather than promoting competition.

As another alternative, a technological paradigm shift can be considered. Under these conditions the technological features of the electricity sector are aligned to the needs of a liberalized market. As a consequence of the institutional unbundling of the sector, the technology needs to be decomposed in order to reduce the interdependency and complementarity of the system. This very challenging task implies that parts of the network can be operated independently from the remaining system. This is possible from a technical perspective. Examples include the idea of an ‘energy web’, which is similar to the internet. Semi-autonous mirco-grids can be independently operated, performing most of the critical technical functions. They are connected to a backbone transmission network for trade or emergency back up. Within the boundaries of the micro-grid it is possible to re-establish the coherence between critical technical functions and critical institutional arrangements. This development requires a radical technological change. The present paradigm of centralized technological system control needs to be changed into a decentral approach. This raises the question about the adaptability and path dependence of the current system. However, this goes beyond the scope of this paper. There are signs that such a change cannot be excluded. There is great interest in certain technologies that potentially constitute an electricity web. Examples include the increasing importance of small-scale decentral power production, the introduction of intelligent meters for residential customers, and power electronics enabling monitoring and control of transmission lines. Under these conditions, regulation would need to stimulate selected technological innovations that enable the realization of such a new electricity system. There might also be some recent political preferences in favour of this concept, related to the threat of terrorism. Decentralized electricity systems are far less vulnerable to terrorist attacks as compared to the present centralized system.

Obviously the challenges for the regulation of liberalized electricity markets are quite different, depending on the long-term vision of the technical development of this sector and the political preferences with respect to the traditional system or an ‘electricity web’. A more detailed analysis could reveal whether in certain countries there are autonomous developments in favour of one or another system.

6 Conclusion

This paper deals with the question whether there is an interrelation between the technological features of the electricity sector and the evolving institutional arrangements of a liberalized market. Starting point of the analysis is the assumption that critical technical functions need to be supported by suitable institutional arrangements in order to safeguard a satisfactory functioning of this infrastructure. The following problem statement is addressed: What are critical technical control mechanisms in the electricity system and how are they related to institutional arrangements that support the technical functioning of the system?

The paper specifies various critical technical functions that are related to aspects of capacity management (operational real time, tactical, and strategic long term), interconnection and interoperability. The degree of criticality of these functions is further operationalized in terms of the time scale in which technological control is required, and the technological scope. The shorter the time scale, the more critical the technical functions. This makes the operational real-time capacity management the most critical. With respect to the scope, all critical technical functions relate to the entire system, which makes them highly critical.

Consequently different institutional arrangements of liberalized electricity markets are elaborated. These are the transmission system, the market for electricity and the firm. The institutional scope of these arrangements appears to be different from the technological scope. This raises the question, whether there is a need for coherence between technological and institutional regimes. The degree of coherence is further operationalized, for instance by different incentive schemes, information flows, different technological and institutional preferences, and agents.

It is argued that there is a necessity to align technological and institutional regimes into a coherent framework in order to develop a sustainable sectorial organization. For supporting the process of institutional and technological change in the electricity sector, two different regulatory approaches are possible. In the first approach the present technology is taken as given, hence institutions need to adapt to the needs of the critical technical functions. Under these circumstances the vertical re-integration of the value chain needs to be supported, rather than the competitive market structure. The ongoing process of economic consolidation and concentration is a development in this direction.

As another approach, technology changes according to the needs of liberalized market structures. This requires a technological paradigm shift towards a decentralized ‘energy web’ that has comparable characteristics as the Internet. Within the technical boundaries of small-scale micro-grids there are opportunities to realize coherence between critical technical functions and critical institutional arrangements. From an empirical perspective there are some developments that might be ingredients of a paradigm shift, including the growing importance of small-scale power production, the evolution of smart meters, and the introduction of power electronic devices that make networks ‘intelligent’.

This paper elaborates some interrelations between technology and institutions, which are often neglected, both by engineers and social scientists. Engineers are mostly concerned with the technical system control, while many economists tend to see the market mechanism as a generic approach to improve efficiency and economic welfare. This case illustrates that the regulation of this important sector needs to take technology explicitly into consideration. It limits the possibilities for market restructuring and hence liberalization. Critical technical functions need to be safeguarded under all conditions. Without a paradigm shift toward a decentralized ‘energy web’, liberalization cannot be sustained on the long-term. In order to make liberalization a success, technology needs to change. The regulation of liberalized markets would not only require to stimulate competitive market structures, but perhaps even more important, to stimulate specific technologies that enable a paradigm shift. Many governments presently favour a regulatory policy of technological neutrality. This is certainly not helpful to stimulate such a paradigm shift.

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