Infrastructure sector characteristics
and implications for innovation and sectoral change

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Abstract

Infrastructure sectors such as energy or water supply, sanitation or telecommunication provide us with services that are essential for modern life and for industrialized societies. In this article, we explore some of the sectors' key characteristics in order to better understand the conditions that stimulate or hinder far-reaching transformation processes in infrastructures. It will be argued that durable and capital intensive assets together with a high degree of systemness generate considerable inertia and rather impede fundamental change. At the same time, capital intensity and massive investment needs as well as negative environmental impacts represent sources for change. A high degree of regulation and an often large share of public utilities also play a key role for sector dynamics. Conceptual frameworks for studying infrastructures and making policy recommendations have to take into account these particularities and the close interplay of techno-economic, organizational and institutional characteristics.

Introduction

Infrastructure sectors such as water supply, electricity supply, sanitation, telecommunication, railway transport or road transport provide basic services for almost any other sector of economic activity and society as a whole. Wealth and welfare crucially depend on these sectors and in most industrialized countries, it has become a matter of course that infrastructure based services are reliable, affordable and of high quality - at any time and almost any place. However, there are major challenges ahead. Massive investments are needed in many sectors to restore existing infrastructures to a good condition and to cope with increasing demand (Gil and Beckman 2009; OECD 2007). Serious environmental impacts call for fundamental changes in currently dominant modes of service provision and consumption, especially in the fields of energy supply and transportation (Clark II and Lund 2008; Hoogma et al. 2002; Unruh 2000). Market liberalization has questioned traditional concepts of service provision and triggered organizational and institutional changes in sectors such as telecommunication and electricity supply (Armstrong and Sappington 2006; Markard and Truffer 2006; Sioshansi 2006a). And also new technologies continuously challenge established socio-technical paradigms - take, for example, the impact of ICT in the telecommunication sector and its potential impacts on other sectors, e.g. in terms of decentralization (Godoe 2000; Nightingale et al. 2003).

Against this background, the transformation of infrastructure sectors and the conditions under which infrastructure systems undergo fundamental changes become key issues for research. In order to achieve more sustainable modes of service provision, for example, far-reaching changes are necessary and therefore it is essential to be aware of the drivers and barriers of transformation in infrastructure sectors. The same holds for the financial challenges ahead. If they are to be addressed by new organizational or institutional structures or by novel technologies (e.g. decentralized sanitation systems that reduce the necessity to install capital intensive, centralized sewer network), we have to understand their origins as well as the potential to achieve radical changes in infrastructures.

With the following we want to contribute to the research agenda on the transformation of infrastructures. Our analysis addresses the question whether infrastructure sectors exhibit certain particularities that play a role in sectoral transformation. It will be argued that, in some respects, infrastructure sectors are quite different from other sectors and that these particularities matter, especially if there is an interest to initiate and govern transformation processes towards a specific end (e.g. sustainability).

Infrastructures and the underlying socio-technical systems have developed over long time frames and turned into large, complex systems with highly intertwined socio-technical, economic, institutional and organizational structures (e.g. Hughes 1983; Kaijser 2005). Far-reaching changes will affect all of these different aspects and therefore have to be analyzed from a systemic perspective. In this paper, we introduce a set of seven key dimensions along which infrastructure sectors can be analyzed. These dimensions include capital intensity, asset durability, environmental impacts, systemness, public organizations, regulation intensity and competition intensity. The dimensions cover techno-economic, organizational and institutional aspects of infrastructure systems and can be used to analyze and compare different sectors - especially in terms of transformation potential. It will be argued that infrastructure sectors are typically characterized by durable, capital intensive assets and a high degree of systemness, which generate inertia and pose barriers for far-reaching transformation. At the same time, massive (re-)investment needs and negative environmental impacts (in some infrastructure sectors) represent sources for change that are often inherent. Furthermore, infrastructure sectors are characterized by a high degree of regulation and an often dominant role of public utilities, which might also affect the dynamics of transformation.

At a more general level, we will argue that the particularities of infrastructure sectors also have to be taken into account when managerial practices, governance concepts or regulatory policies that have been successfully applied in other contexts are about to be transferred. Analytical concepts and subsequent recommendations, in other words, have to be well adapted to the sectoral context they are applied to (Flyvberg 2001). Research on infrastructure sectors has to acknowledge, for example, the strong influence of sector-specific regulation and the key role of public organizations pursuing a variety of, sometimes conflicting, political objectives. In a similar vein, our concepts have to take into account the systemic nature of infrastructures and the close interplay of technical, institutional and organizational elements (e.g. Finger et al. 2005; Künneke et al. 2010).

It has to be noted though that while analyzing the commonalities and particularities of infrastructure sectors we do not want to downplay the fact that there are also many differences among the different sectors and also among countries. The general reflections we provide in this paper can offer some guidance on the general characteristics of infrastructures but they can of course not substitute for individual analyses of specific sectors, countries and times. Furthermore, we do not claim that sector characteristics are the only factors that affect transformation. New technological developments, product innovations, a worsening of public finances or new waves of market liberalization for example, can represent additional drivers of sectoral change (Markard and Truffer 2006).

The text is structured as follows. The next section provides an overview of key issues of research on infrastructures with a particular focus on how transformation processes are conceptualized. Then we define infrastructure sectors and discuss how they can be delineated from other service sectors. Following that, we introduce seven key dimensions to analyze the particularities of infrastructures and we compare very roughly how major infrastructure sectors compare along these dimensions. On this basis it is finally discussed how the characteristics of infrastructures influence the sectors' propensity to undergo far-reaching changes.

Different approaches to research on infrastructure sectors

In the literature, infrastructure sectors have been studied from different perspectives. Taking a *technological perspective* is the traditional approach to research on infrastructures - adopted primarily by engineers to tackle the broad range of technical challenges related to the design and improvement of physical components, for example, the optimization of the interplay of these components or the development and implementation of new technologies. And even aspects with less of a technology focus such as infrastructure planning, project management or environmental impact assessment have been addressed from this perspective. However, the influence of the classical engineering perspective in infrastructures is waning (Grigg 2001) and it is more and more complemented by insights from other disciplines such as economics or management studies.

Of particular prominence here is the *regulatory perspective* that deals with the regulation of natural monopolies in infrastructure sectors (e.g. Brunekreeft 2009; Guthrie 2006; Künneke 1999; von Hirschhausen et al. 2004). The general concern here is to improve economic efficiency of infrastructure based service provision. Against this background, especially the issue of market liberalization, i.e. the introduction of competition in sectors that were traditionally organized as regulated monopolies has gained a lot of attention in recent years - both in the scholarly literature and in real-world policy making (e.g. Armstrong and Sappington 2006; Jamasb and Pollitt 2005; Sioshansi 2006a). Closely related key topics are the vertical unbundling of utilities and privatization (e.g. Dore et al. 2004; Kessides 2004; Weizsäcker et al. 2005).

Infrastructure sectors are also studied from a *management perspective* although this is still a young field of inquiry. Organizational capabilities, strategic planning (Dominguez et al. 2009; Dyner and Larsen 2001), project management, long-term investments, public private partnerships (Kwak et al. 2009) and risk management (Larsen and Bunn 1999) are some of the key issues in this emerging strand of research (Bausch and Schwenker 2009; Gil and Beckman 2009).

While each of these perspectives has its merits, there is a risk that certain processes or effects are in the spotlight while others are neglected, e.g. due to different ontological assumptions in different strands of literature (cf. Geels 2010). The technological perspective might miss economic and regulatory implications, for example, and vice versa. In infrastructure sectors, technical components are often highly interrelated and a proper coordination and functioning of the systems requires organizational and institutional structures that take these particularities into account (Finger et al. 2005; Künneke et al. 2010). Against this background we argue that an encompassing analysis of infrastructure sectors has to be based on a systemic view. Such a holistic approach is all the more essential for studying processes of transformation and change.

Analyzing the transformation of infrastructures

Sector transformation as we will use the notion in the following refers to far-reaching and encompassing changes in the sense of socio-technical transitions (Geels 2002; Kemp and Rotmans 2005; Smith et al. 2005) but also to major institutional or organizational shifts which are not accompanied with fundamental changes in technology. An example for the former would be the decentralization of sanitation or electricity supply (Larsen et al. 2009; Verbong and Geels 2007), while the liberalization of telecommunication and energy markets stands for the latter (Sioshansi 2006a; Teece 1998).

In the field of science and technology studies, there are at least two holistic approaches to studying and explaining the transformation of socio-technical systems in general and infrastructure sectors in particular. The *large technical systems* (LTS) framework, which was developed on the basis of studies on the historic development of electricity supply (Hughes 1983), emphasizes that physical components, organizations and institutional structures in such systems are highly interrelated and have co-developed over time in processes of social construction (e.g. Hughes 1987; Joerges 1998; Kaijser 2004; van der Vleuten 2004). Following Hughes (1987), large technical systems develop momentum, i.e. they have a tendency to continuously grow (increase of sales volume, expansion in space, integration of services along the value chain). System expansion, however, is time and again hampered by bottlenecks or reverse salients, which arise because the relationships between system elements change and create conflicts in the course of the expansion process. Efforts of actors in the system are then said to concentrate on solving the problems, which is why reverse salients trigger incremental or radical innovation. In the electricity sector, for example, wide-spread dependency on oil-fired power plants turned out to be a reverse salient at the time of the oil crises in the early and late 1970s and - together with other factors - contributed to the development of nuclear power technology (Hadjilambrinos 2000; Markard and Truffer 2006).

With its stylized explanations (momentum, load factor, reverse salients), the LTS framework highlights the role of system inherent or *internal processes of change* and adaptation. In fact, it is even argued that system expansion is driven by the intention to internalize and control former external developments (Hughes 1987). However, the LTS approach is less capable of explaining the possibly disruptive effects of external developments and whether sectors might ‘react’ differently to such external pressures (Smith et al. 2005). Take, for example, fundamental changes in the price of input factors (e.g. oil crisis, see above) or technological advances that confront the established technologies of the system. A case at hand is the development of gas turbines in the aircraft industry, which were later applied (and developed further) for electricity generation (Islas 1999).

The *multi-level perspective* is an alternative framework for explaining fundamental changes in socio-technical systems based on evolutionary theorizing (Geels 2002; Rip and Kemp 1998). It takes such external sources of change explicitly into account Following this perspective, developments at a macro level, the so-called landscape, may exert considerable pressure on existing sectors, or socio-technical regimes, thus creating room for technological innovations to diffuse and even overthrow prevailing system configurations (Geels and Schot 2007). In the electricity sector, high rising oil prices in the 1970s and 80s can be interpreted as landscape pressures that - together with other developments - contributed to the emergence of nuclear power and wind power as technological alternatives (Markard and Truffer 2006).

Like the LTS approach, the multi-level perspective emphasizes the stability and inertia of established socio-technical systems or regimes. Technological configurations, organizational structures and institutions (rules) at the regime level have co-developed over time and through this process they have achieved a high degree of complementarity and interdependence that poses significant barriers to transformation. In the multi-level framework, far-reaching changes in regime structures (transitions) are triggered by landscape forces (see above) and by competing technologies that have developed in niches. These niches are spaces in which radically different technologies or products are protected from the selection pressures of the regime (e.g. Hoogma et al. 2002; Kemp et al. 1998).

The multi-level perspective has been applied to a variety of cases in which technological transitions were observed in the past. In the field of infrastructure sectors, examples include the establishment of water supply and sewer systems in the Netherlands (Geels 2005; Geels 2006), a study on the interaction of different infrastructure sectors (Konrad et al. 2008) or several analyses on emerging technologies and potential transitions in the energy sector (Raven 2006; Raven and Verbong 2007; Verbong and Geels 2007).

To summarize, research on the transformation of infrastructures should be based on a multi-dimensional approach taking into account the systemic interplay between technical, organizational and institutional structures. In addition to that, (internal) dynamics at the sectoral or system level as well as external developments can be expected to play a role. External dynamics encompass developments at the landscape level or in technological niches but also in related sectors. In this regard, interactions between different infrastructure sectors might be especially important (Kaijser 2004; Konrad et al. 2008). Finally, we also have to pay attention to the particularities of infrastructures. Several studies have already emphasized the highly systemic nature of infrastructure based service provision and the complementarities between e.g. technological and institutional structures (Finger et al. 2005; Jonsson 2000; Jonsson 2005). It is especially the latter aspect that is important, e.g. with regard to the development of regulatory recommendations or management concepts for infrastructure systems. Whenever concepts are about to be transferred to a different context (here: sector), there is an inherent risk that the assumptions on which the concept is based might not apply in the new context (Flyvberg 2001). This is why in the next sections we take a closer look at the particularities of infrastructure sectors and how to compare them.

Defining and delineating infrastructure sectors

In order to elaborate on the characteristics of infrastructure sectors, we first have to specify how we define and delineate these sectors. Finger et al. (2005), for example, refer to infrastructures as "... very complex technical, economic, and political systems that provide essential services to society." (p.228). And from a technical point of view, Jonsson (2000) conceptualizes a so-called *infrasystem* as "... a network of links and nodes housing a certain flow that moves through the network links and is processed in the network nodes" (p. 84). We view two aspects as important here. Infrastructures provide services that are essential for society (Finger et al. 2005; Kaijser 2004) and they do not just comprise physical artifacts but also people, organizations, knowledge and economic and legal conditions (Hughes 1987; Jonsson 2005; Kaijser 2004).

In the following, we will concentrate on sectors and services that are based on physical networks in the sense of transmission and distribution grids. We propose the following definition for network based infrastructure sectors.

> *Network based infrastructure sectors are those sectors of economic activity that provide services of fundamental importance for society by means of physical networks (interconnections). An infrastructure sector encompasses technologies, physical elements such as pipelines and plants, organizations such as utility companies, suppliers and public authorities and institutions such as regulations for grid access or quality norms.*

A challenge of this definition is certainly being able to draw a line between fundamental (or essential) and less fundamental services. Different kinds of consumers may have different views on that and we also expect that this perception differs among people with different cultural backgrounds for example. Moreover, society's perception of importance might change, e.g. increase over time. Also note that we do not use the notion of network industries here because industries are often regarded as firms competing in a specific market. With sector or system, we refer to broader organizational fields with different sub-markets (e.g. upstream technology development, plant operation or end user service provision).

Infrastructure based services fulfill basic human needs such as drinking water, personal hygiene and health, mobility or communication (cf. Jonsson 2005). The way in which these needs are fulfilled have become more and more sophisticated over time so that infrastructure service provision is now *convenient*, *reliable* and *cheap* (ibid.) - at least in most industrialized countries. The needs also have changed. Consumption levels have increased dramatically over time and today, almost all of our private and business activities, technologies, products and other services heavily depend on infrastructure services. As a matter of fact, it has become very *difficult to substitute* them. Take electricity supply for example: while it can be substituted in principle (e.g. by gas light) or supplied in a different way (e.g. by roof-mounted solar panels), these alternatives have essential shortcomings as they are less convenient, less reliable or more costly. It has to be noted though that these shortcomings are not absolute but an expression of how established technologies and user needs have co-developed over time and shaped each other.

< insert Table 1 here >

Table 1 lists those network based sectors that provide services of major importance for society. The sectors are grouped according to basic functions they fulfill: water management, energy supply, transportation and communication.

< insert Table 2 here >

There are also other sectors that contribute to these general functions. Examples include drainage and flood control (water management), petroleum supply (energy supply), air and sea transport, mail services, mobile telephony or radio and TV (communication / information). As they are not, or just in parts, based on physical networks, we have arranged them in a separate Table 2. To this list, we also added a broad range of additional service sectors fulfilling functions such as (health) care, protection, education or financial services.

Many of these can also be classified as *public service sectors* with services provided or mandated by public authorities (e.g. municipalities, the state). Public service sectors typically provide merit goods, i.e. commodities that fulfill the basic needs of individuals or a society. In this regard there is often an overlap with network based infrastructure sectors, i.e. many infrastructure sectors are dominated by public service providers. We will elaborate on the reasons for that below. It has to be noted though that 'pure' public sectors are rather an exception. In many cases, there is a mix of public and private organizations involved in service provision. The list in Table 2 is not comprehensive. It serves as an illustration for the broad range of other sectors that are similar to infrastructure sectors - as they are organized similarly or fulfill related functions.

Key dimensions for the analysis of infrastructure sectors

In general, economic sectors can be analyzed and classified from a variety of angles. Which dimensions are chosen depends on the purpose of the analysis. In order to compare markets for example, one might take a closer look at firm size and market concentration, the degree of competition or the structure of the value chain (e.g. in terms of vertical integration). Another example is Porter's (1980) five forces framework, which was developed to assess the attractiveness of an industry from a business perspective. For our purpose of analyzing the sectoral particularities that influence transformation processes, the analytic dimensions have to be generic, i.e. we have to include techno-economic, organizational and institutional aspects (cf. theory section). Techno-economic characteristics refer to the physical elements and the nature of the technologies that infrastructures are based on. Organizational characteristics point to the actors (firms, public authorities etc.) and the way service provision is managed. Institutional characteristics refer to the rules that determine the interplay of actors as well as of actors and technologies. These three general dimensions are also prevalent not only in the LTS literature (see above) but also in research on technological systems and systems of innovation (e.g. Carlsson and Stankiewicz 1991; Malerba 2002).

In the following, we elaborate on seven specific sub-dimensions. The dimensions were selected because we expect them to affect transformation processes in infrastructure sectors (e.g. as they point to sector characteristics that represent barriers or drivers for change) and because they highlight the specific nature of infrastructures (e.g. in comparison to 'conventional' service sectors, see below). However, we do not claim that the dimensions are the only possible framework for this kind of analysis. Techno-economic dimensions include capital intensity, asset durability and environmental impacts. Capital intensity and asset durability capture key characteristics of the technological core (infrastructure networks). Environmental impacts was selected as one of the key drivers for change. In order to represent organizational characteristics, we propose to analyze the degree to which public organizations are involved in service provision. Public control over utilities is motivated by the societal importance of infrastructures and we assume that the underlying political influences are also essential for transformation processes. As institutional sub-dimensions we selected regulation intensity and the degree of competition in a sector. The former is again related to the societal importance of service provision, while the latter is linked to the prevalent issue of natural monopolies in network sectors (see below). Both dimensions strongly reflect the specific nature of infrastructures that sets them apart from 'conventional' sectors. From the organizational and institutional characteristics of infrastructure sectors we expect significant moderating effects on the way in which sectoral change unfolds and what kind of 'frame-conditions' play a role.

Each dimension will be introduced and discussed below. This also includes an indication of how to determine whether a sector scores high or low on one of these dimensions.

Capital intensity

If capital costs have a major share in the overall costs of service provision, an infrastructure based service is classified as capital intensive. High capital costs are typically related to physical assets such as transmission networks, pipelines, power plants, treatment plants etc. Network sectors are often capital intensive as they are based on widely expanded physical networks as well as large centralized plants or stations. A major consequence of capital intensity are fixed costs, which are independent of the actual use of the network. In sanitation, for example, fixed costs are responsible for about 80% of the total costs (Maurer et al. 2005). In the electricity sector, especially nuclear power plants and renewable energy power plants are characterized by a high share of fixed capital costs.

In economic terms, capital intensive infrastructures result in *natural monopolies*, i.e. the first supplier has an overwhelming cost advantage over potential competitors because his marginal costs are far below the average costs that his competitors have to take into account. Natural monopolies imply the risk that the monopolistic supplier realizes rents much above what can normally be expected. This is one of the reasons why many network based services are strictly regulated and / or provided by public utility companies (see below). Another consequence of capital intensity and fixed costs is that if they are reflected by price structures this creates incentives for high levels of consumption, which pose problems if consumption causes negative external effects e.g. in environmental terms (see below).

Asset durability

A second key dimension is the durability or useful life of the physical assets. Asset durability is considered to be high if it is in the range of decades, which is a long time span compared to investments in much of the business world. Infrastructure sectors are often based on assets with a high durability. In electricity supply, for example, nuclear power plants have a useful life of around 30 years, while hydropower stations can often be operated for almost 80 years without major re-investments. Power lines last about 40-60 years and sewers can again reach a useful life of 80 years before they have to be replaced (Maurer et al. 2005). High asset durability decreases capital intensity to some extent. Highly durable assets are favorable because investments can be depreciated over long periods. However, they also come along with considerable uncertainties as the frame conditions, under which investments were made, can fundamentally change over such long time spans (Dominguez et al. 2009).

Environmental impacts

Environmental impacts of infrastructure based services may be substantial and can even negatively affect processes at the global scale. In the case of power supply, depletion of fossil fuel resources, air pollution or production of nuclear waste are examples of negative impacts associated with the consumption of electricity generated by fossil fuels or nuclear energy (e.g. Markard and Truffer 2006; Unruh 2000). Similar impacts are caused by gas supply for example. It is quite a challenge if not impossible to aggregate the different environmental impacts (e.g. across scale, time and type of impact). Let us assume, however, that we were able to determine environmental costs as a measure of the environmental impact of a particular service. If these costs make up a crucial share of the overall costs for service provision, the environmental impact of an infrastructure sector can be regarded as high. A consequence of the environmental impact of infrastructure based services is that there are many regulations in place to mitigate negative impacts (see below).

Public organizations

Due to the societal importance of infrastructure based services and the monopolistic character of the underlying networks, public organizations often play an important role as service providers in infrastructure sectors. However, this is not necessarily the case. Moreover, the degree to which public organizations are involved in service provision varies. Recent sector reforms in electricity supply or telecommunication for example, were in many countries accompanied by a vertical disintegration (unbundling) and privatization of service providers, which has led to quite distinct changes in many cases (e.g. Bartle 2002; Joskow 1998). The degree of public organizations in a sector can be defined as high, if a large share of the market is served by public utilities. Public utilities are either corporations with (a majority of) public shareholders or organizations that are directly controlled by a municipality, for example. The former may exhibit management structures comparable to private firms, while the latter are closely related or even integrated into public administration.

What matters here is not so much the issue of property rights but of decision rights: Strategic decisions in public utilities (e.g. strategic positioning, major investments, pricing, new business fields) may strongly be influenced by public authorities and policy makers.

This is often intended and the rationale is to realize *political objectives* by direct public involvement in service provision (e.g. in addition to regulation). Political objectives can be manifold including for example, low prices, little or no regional price disparities (e.g. rural vs. urban areas), environmental objectives that exceed legal obligations, local autonomy and independence, regional development, cross-subsidizing between other public services etc. We suggest paying attention to the degree of public organizations to realize the potential influence of multiple political objectives on both strategic decisions at the organizational level and developments in the sector as a whole. Put differently, public organizations may well be different from private firms and standard assumptions related to firm behavior, e.g. in terms of profit orientation, may not fully apply.

Regulation intensity

Regulation intensity refers to the degree of regulation in a sector. A sector is considered to be regulation intensive if a broad range of aspects, i.e. network access, network pricing, price and quality of the service, safety issues, environmental impacts etc. are publicly regulated. We expect that infrastructure systems are typically characterized by a high degree of regulation and that even processes of market liberalization are often accompanied by intensive re-regulation (cf. Armstrong and Sappington 2006). With this dimension we want to draw attention to fundamental differences between infrastructures with a set of sector specific regulations and other sectors that are just subject to competition policy (see also Walz 2007 in this regard). As with public organizations, we argue that there are particularities that matter although we do not claim that regulation affects sectoral transformation in a specific way. Regulation intensity is caused by the fundamental importance of infrastructure services as well as their capital intensity and the resulting natural monopolies. With regard to the former aspect, regulators have to make sure that service provision is in line with political (or societal) objectives such as affordable price, sufficient quality, high security of supply etc. With regard to the second aspect, network access and pricing have to be regulated in order to prevent monopoly rents. In regulated monopolies, the price for a specific infrastructure service is regulated, while in liberalized markets the focus is on network regulation and unbundling (e.g. Armstrong and Sappington 2006; Jamasb and Pollitt 2005; Teece 1998; von Hirschhausen et al. 2004). Finally, there is a third driver for regulation intensity in those sectors that cause severe environmental impacts: here regulation is applied in order to reduce these impacts or keep them within certain limits (Rennings 2000; Walz 2007).

Competition intensity

The sixth dimension we propose is related to the degree of competition in a sector. In situations where market entry barriers are low, rivalry among competitors is high and substitute products threaten the market competition will be intensive (cf. Baumol et al. 1982; Porter 1985). Transferred to infrastructure sectors, competition intensity is said to be low if consumers have only one supplier or product to choose from and it is high if consumers have the choice among different products and switching rates are high. While intensive competition is a characteristic of many 'conventional' industries, infrastructure sectors are rather different in this regard as many of them are organized as regulated monopolies (see above). In some sectors, it may be possible to unbundle the value chain of service provision and to operate the network as the most capital intensive part of the infrastructure separately from other major services (e.g. sales & customer care, trading, power generation). While network operation then remains a (natural) monopoly business, other parts of the value chain can be opened up for competition. Since the 1990s, especially telecommunication and electricity supply have been re-organized in that way in many countries (e.g. Sioshansi 2006b; Teece 1998) and as a result, competition intensity has often increased. A key driver behind this wave of market liberalization was the influence of a neoliberal policy agenda that made economic efficiency (to be achieved by competition) the top goal for organizing all sectors of economic activity - including infrastructure sectors (Bartle 2002).

Systemness

The seventh and final dimension is the systemic character a sector exhibits. Systemness is considered as high if there are strong interdependencies and complementarities among system components, which means that they cannot function without each other and overall system performance is highly dependent on how well the various components are coordinated (cf. Hughes 1987; Kaijser 2004; van der Vleuten 2004). There might be critical assets (and related critical functions) that are central for system operation and management and therefore should receive particular attention with regard to the question of how they are dealt with in organizational or institutional terms (Finger et al. 2005; Künneke 1999). Some infrastructure sectors, e.g. electricity supply, railway transport and telecommunication are characterized by strong interdependencies between their various elements, or a high degree of systemness. In other network sectors such as road transportation for example, these interdependencies are less prominent, although they still exist (see below).

The systemic character entails that by changing one element, other elements have to adapt and change as well. A novel product or technology, for instance, must not only meet consumer needs but it must also be compatible with the existing network structure and with technical norms (e.g. Photovoltaic installations). Furthermore, complementary organizational and institutional structures need to be developed (e.g. business models for operating decentralized plants or grid access priority for renewable energies). Such changes might again lead to frictions in the system.

The seven dimensions introduced above are relevant when studying the transformation of infrastructures. If a selected sector scores high on some or all of these dimensions then we expect that this will have an effect on the sector's general propensity to change and on how change will unfold. We will elaborate on this in section 6. At the same time, the dimensions also highlight the particularities of infrastructures, which set them apart from other commercial sectors. These specificities are relevant for the conceptual frameworks we apply for the analysis of infrastructures. In situations characterized by a high degree of specific regulation and little competition, for example, transformation dynamics will be very idiosyncratic and experiences from other contexts might be difficult to transfer.

How do the dimensions relate to each other? The existence of physical networks and the high societal importance of infrastructure sectors tend to influence how infrastructure sectors score on some of the dimensions. Societal importance, for example, has driven direct involvement of public authorities in service provision through public utilities and the often prevalent high degree of regulation. However, this relationship may be visible to varying degrees and recent liberalization processes have considerably increased the variety of infrastructure governance. We therefore argue that it is an empirical rather than a conceptual question of how the dimensions are connected. In conceptual terms, there are no direct dependencies.

Characteristics of infrastructure sectors

From the arguments presented above we can expect that infrastructure sectors exhibit common patterns along several of the seven dimensions. Yet to what extent is this really the case? How do different sectors compare along the dimensions? As there is considerable variation among sectors, countries and regions we cannot expect an answer that holds true for all situations. However, what we sketch here is a very rough picture of the key characteristics of selected infrastructure sectors to support our broader line of argumentation that many of these systems exhibit certain particularities that have an impact on sectoral transformation. The idea is to provide a general impression without addressing the existing variation (e.g. among countries) in detail.

< insert Table 3 here >

Table 3 depicts how major infrastructure sectors compare along the seven dimensions with an ordinal ranking of four classes on each dimension. The values indicate some kind of ‘average characteristics’ that apply in many industrialized countries. For each dimension we apply the criteria introduced above. Note that this assessment is based on an educated guess resulting from our knowledge of these sectors and not on a more systematic analysis such as a comparative survey of different countries. Medium and dark shaded fields indicate high and very high marks except for competition intensity, which was colored inversely. The underlying idea is that the shading indicates deviation from characteristics one would expect in more ‘conventional’ service sectors such as financing, consulting or entertainment. The dimensions are sorted according to a descending number of high marks.

The comparison shows that the seven selected infrastructure sectors are characterized by a high or very high degree of capital intensity, asset durability and regulation intensity. The sectors also tend to exhibit a considerable degree of systemness, although road transport is an exception here because physical infrastructure provision and actual services (individual transport, bus transport, freight transport etc.) are decoupled. There is less of a common pattern in the latter three dimensions though. Water supply, sanitation, railway transport and road infrastructure are typically characterized by a high share of public organizations, while there is less dominance of public utilities in energy supply and telecommunication. In terms of competition intensity the pattern is similar: competition is often low but telecommunication, electricity supply and, to some extent, also gas supply have been opened up for competition in recent years (see above). With regard to environmental issues, finally, the two energy supply sectors exhibit considerable impacts while for most of the other sectors it is less of an issue.

In summary, infrastructure sectors typically exhibit a high degree of capital intensity, asset durability and systemness and they are often characterized by intensive, sector-specific regulation. Furthermore, sectors such as water supply, sanitation and railway and road transportation are characterized by a dominance of public organizations and little competition as they are governed as regulated monopolies.

< insert Table 4 here >

How do these characteristics compare to other service sectors? Public sectors in the fields of (health) care, education or security services (cf. Table 2) are certainly similar to infrastructures with regard to an often high degree of public service providers. They also exhibit similarities in the institutional dimensions: little or no competition and a considerable degree of specific regulation. The aforementioned public sectors are different though in terms of their techno-economic characteristics: capital intensity, asset durability and also a high degree of systemness are less of an issue here (cf. Table 4).

Another set of sectors are those that fulfill the same general functions as infrastructures (energy supply, water management and transport) but are not based on physical networks. These include oil supply, flood control, air transport or sea transport. In these fields, we expect certain similarities with infrastructure sectors in terms of capital intensity and asset durability. This would point to the fact that some sector characteristics are influenced by the socio-technical nature of the underlying service. Most in contrast to infrastructure sectors, finally, are ‘conventional’ service sectors such as financial services, consulting or entertainment. These sectors are characterized by a low degree of capital intensity and asset durability, mostly private firms, high competition and often little sector specific regulation (cf. Table 4).

Impact of sector characteristics on transformation

In this section, we discuss how the particularities of infrastructures affect transformation processes in these infrastructure systems. Generally, sectoral change in infrastructures is affected by a large variety of ‘factors’ (Markard and Truffer 2006) many of which are external, i.e. they cannot be influenced by actors in the sector. Market liberalization, for example, is such an external driver of change (Markard et al. 2004). The following analysis concentrates on internal influences that are related to specific sector characteristics. We will distinguish between barriers and drivers of change as well as ‘moderating factors’.

Sector specific barriers for change

The highly systemic character of infrastructures represents a very significant barrier for transformation because changes in one part of the system also affect the other parts (see above). In technical terms, for example, novel technologies have to fit into the existing structures (e.g. with regard to grid connection) as long as the latter are dominant. As a consequence, extra costs arise for achieving technical compatibility thus slowing down innovation diffusion. Moreover, not only technical components of infrastructure systems but also technical and non-technical structures are highly intertwined (cf. infrastructures as socio-technical regimes), which means that besides the technical fit also organizational and institutional compatibility are required (Finger et al. 2005). Transformations in infrastructures therefore tend to be incremental rather than radical and path-dependencies are to be expected (Markard and Truffer 2006).

Moreover, durable and capital intensive assets lead to a considerable degree of inertia and resistance to change. Actors who have invested into infrastructure have a strong interest to make profits from depreciated assets as long as possible. In sectors that grow slowly or stagnate, technological innovations (e.g. novel types of power plants) will only diffuse gradually over time as they replace decommissioned units. Under these circumstances, far-reaching technological changes in infrastructures may take decades. Exceptions are places where infrastructures are still expanding (e.g. rapidly growing cities). Such contexts may represent niches in which novel technologies can be applied, tested and improved so that they are later also adopted in less dynamic contexts (e.g. Binz and Truffer 2009). In well established sectors, however, also organizational structures (e.g. business models, market structures, dominance of specific firms) and institutions tend to be rather stable to the degree that they are well adapted to the existing technological configurations. Conversely, incumbent firms are often reluctant to commit themselves to technologies that require different business models or deviate from established professional standards. This was one reason among others for the slow uptake of wind power by German utilities (Stenzel and Frenzel 2008).

Sector specific sources for change

The two most prevalent sources for change are massive needs of re-investment and negative environmental impacts. In the past, many infrastructures have not been maintained or renewed adequately, which today leads to increasing failures and an accumulation of investment needs (Gil and Beckman 2009). For developed and emerging economies, the OECD estimates that up to $53 trillion will be needed to update and develop electricity, water and transportation infrastructure until 2030 (OECD 2007). Such massive investment needs contribute to changes in two respects. In technological terms, they open windows of opportunity for an encompassing replacement of existing technologies and artifacts with less capital-intensive alternatives. As a matter of fact, even the prevailing socio-technical paradigm of a capital intensive, centralized infrastructure may come under pressure. In the case of sanitation, for example, we may think about semi-decentralized treatment solutions for multi-story buildings or newly constructed housing areas (Larsen et al. 2009). Such systems would make sewers redundant (reduction of investment needs) and could even operate without water (reduction of natural resource needs). In organizational terms, massive investment needs may foster mobilization of new sources of financing especially from private investors. Privatization of infrastructures or public private partnerships are therefore a major aspect of transformation in many infrastructure sectors (e.g. Gil and Beckman 2009)

However, we still have to address the question of why such massive re-investment needs have occurred in the first place. Although there is no general answer to this and situations across sectors and countries are well different, some reasons for under-investment can be traced back to infrastructure characteristics. First, due to a high degree of durability, there is some leeway regarding how and when to renew the physical elements (power plants, networks, streets, bridges, railway tracks). Second, due to a high degree of capital intensity, there is a risk that service prices are primarily oriented at variable costs and do not fully cover the overall costs, including those for infrastructure renewal. The challenge here is that the postponement of continuous renewal or an inadequate pricing of services might be driven by the political objective to keep service prices (temporarily) low. But even if there is a political will to stimulate continuous re-investments, it is a challenge to set regulatory incentives in a way to achieve this aim (von Hirschhausen et al. 2004).

Another source of change are environmental impacts although their importance differs across network sectors (cf. Table 3). Where infrastructure based services are coupled with negative environmental impacts, they may come under pressure because some stakeholders or even the wider public ask for a reduction of these impacts. In some cases, the impacts can be reduced by additional technologies that leave the core of the corresponding system unchanged. Typical examples are end-of-pipe technologies such as the desulphurization of coal fired power plants by advanced filter technologies in the 1980s and 90s or recent advances in carbon capture and storage. However, there are environmental impacts that relate to the very core of supply services as it is the case for CO_2 emissions associated with fossil fuel based energy supply (Unruh 2000). Environmental pressures in this case may lead to a substitution of established technology paths and a more fundamental transformation of the power supply sector, for example (e.g. Markard and Truffer 2006; Raven 2006).

Organizational and institutional particularities and sectoral change

Strategies of firms certainly also play a key role with regard to the propensity of a sector to change. According to Pavitt's (1984) taxonomy of typical innovation patterns at the firm level, infrastructure service providers may be classified as supplier dominated firms. Such firms have little or no in-house R&D but rely on specialized suppliers for novel equipment and technology (Pavitt 1984). Accordingly, novel technologies do not emerge so much from within the sector but are developed elsewhere or as a cooperative endeavor between utility companies and technology suppliers (e.g. Jacquier-Roux and Bourgeois 2002). In the case of electricity supply, the combined-cycle gas turbine technology, which originated and matured in the aircraft industry, is an example of that (Islas 1999; Markard and Truffer 2006). Interestingly, this technological innovation was also accompanied by organizational changes because in liberalized market environments, it significantly lowered entry barriers for newcomers in the form of independent power producers (Winskel 2002). Against this background, utility service providers in infrastructure sectors do not seem to turn into important sources of technological change and transformation. However, they might develop further into information-intensive firms relying on advanced data processing that can be found in banking or tourism, for example (Archibugi 2001). It has to be noted, however, that the transfer of Pavitt's taxonomy to infrastructure sectors may be compromised to some extent because it has been empirically derived from sectors characterized by a high degree of competition.

In organizational terms it is also important that some infrastructure sectors are dominated by public utilities with a strong influence of policy makers on strategic decisions. Under such circumstances, utilities operate differently compared to private firms as they pursue a broader set of strategic objectives. It is often not primarily profitability or shareholder value that matters but broader societal goals such as a low price of service provision, positive effects on regional development, environmental issues or local autonomy (cf. Dominguez et al. 2009). This particularity certainly moderates processes of transformation but it is not possible to make assumptions about how it affects the sectors' propensity to change.

Finally, also the high degree of regulation moderates sectoral change. And again, it is not sensible to draw general conclusions about whether it rather contributes to transformation or creates inertia. One might assume that regulation hampers innovation but especially in the case of environmental technologies, regulation also has proven to be one of the key drivers for innovation (e.g. Markard and Truffer 2006). More important is therefore the general insight that regulation plays a key role for innovation and transformation processes in infrastructure sectors (e.g. Walz 2007). This is certainly a major difference in comparison to fields such as electronics, biotechnology or nanotechnology often studied by technology and innovation scholars. Due to the importance of regulation, also non-firm actors, especially policy makers and the wider public as well as NGOs and professional associations are key players in processes of innovation and transformation.

Conclusions

The analysis has shown that infrastructure sectors exhibit particular characteristics, which differentiate themselves from many other service sectors. These include a high degree of capital intensity, long lifetimes of physical assets, an often dominant role of public utilities, intensive, sector-specific regulation and a high degree of systemness. Furthermore, some infrastructure sectors are also characterized by little or no competition among service providers. This broader picture, however, does not apply to every situation. Individual sector characteristics might well deviate depending on which country, regions or sector we are looking at. The characteristics of infrastructures have also changed over time (e.g. in terms of market liberalization and competition) and continue to do so.

The aforementioned sector characteristics have implications for the transformation of infrastructures. At the sectoral level, techno-economic, organizational and institutional structures have co-developed over long time spans and today, they are highly intertwined and exhibit a considerable degree of systemness. Systemness together with high capital intensity and asset durability represent barriers to far-reaching changes. As a consequence, infrastructures typically evolve gradually and with only incremental changes along established paths (path-dependency). Socio-technical transitions, e.g. towards more sustainable modes of infrastructure service provision therefore will be even more challenging than in ‘conventional’ sectors (which are also characterized by resistant socio-technical regimes).

However, continuous under-investments facilitated by the same sector characteristics as well as environmental impacts related to the nature of the service and the applied technologies, represent important sources for change - at least for some sectors and in some countries. Transformations triggered by these sources will rather be fundamental and thus lead to socio-technical transitions and substantial re-configurations of sector structures. Whether such far-reaching changes occur and how they unfold also depends on a range of external developments like, for example, a worsening of the financial situation of public authorities, the emergence of new technologies, new waves of liberalization or changes in macro-economic conditions (cf. Dominguez et al. 2009; Markard et al. 2004). Such external developments in fact might have a very strong impact on transformation at the sectoral level. The political will to develop and establish nuclear energy technology (Hadjilambrinos 2000; Markard and Truffer 2006) or the technology driven ‘dash for gas’ (Islas 1999) in the electricity sector are examples here. It was beyond the scope of this paper to also analyze these external influences in detail though.

The analytical framework and the seven dimensions we have developed in this paper can be used to analyze (and compare) infrastructure sectors in a more detailed way and in specific contexts. It thus represents a building block in the broader field of research on the transformation of infrastructures. In further studies, we see room to develop the dimensions further, e.g. in order to increase the possibilities for differentiation. In organizational terms, a closer look at vertical integration (or unbundling of utility services) might be promising and in technological terms, a comparison of technological variety (as a precondition for transformation) may generate interesting results. Applying the framework to specific sectors and actual transformation processes will also improve our understanding of how the influence of sector characteristics compares with other factors. It also has to be noted that we do not claim that the seven dimensions are the only way to systematically analyze the sector-specific factors that affect transformation. The framework represents a starting rather than an endpoint for these kinds of analyses.

Apart from their influence on sectoral change, the particularities of infrastructures identified above also have implications for the concepts we apply to these cases. Strategic decision making in public organizations, for example, might well be different from what can be expected in the case of private firms. Political objectives that go much beyond (or even are in contrast to) profitability and economic efficiency may play a role. In a similar vein, the strong influence of sector-specific regulations points to a key role for policy makers 'in the game'. Such particularities have to be reflected in the conceptual frameworks we apply. In other words, a straightforward transfer of theories and management concepts developed and applied in other service sectors or in industries such as electronics, biotechnology, nanotechnology or ICT might be hampered by the particularities we are facing in network sectors. Not only frameworks for innovation and transition studies but also concepts for informing regulation and organizational strategies therefore should be adapted to the particularities of infrastructures in general and, of course, to each sector or situation in particular. If such conceptual transfers are carried out in a conscious and thorough way then we can expect that the particularities of infrastructures will in the end stimulate conceptual improvements whose benefits will reach beyond the field of infrastructure based services.

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Table 1: Network based infrastructure sectors

	General function provided
Water supply, sanitation	Water management
Power supply, gas supply	Energy supply
Railway transport, public transport (streetcars, subways), road transport (provision of road network)	Transportation
Landline telephony, internet service	Communication / information

Table 2: Examples of other service sectors

General function provided	Examples
Water management	Drainage and flood control, waterways
Energy supply	Petroleum supply, district heating[1)]
Transportation	Air transport, bus transport, road transport (services), sea transport
Communication / information	Mail service, mobile telephony, radio, TV[1)]
Waste management	Waste disposal (household, industrial, hazardous waste)
Security / protection	Fire brigade, police, military services
Care	Health care, public housing, elderly care, child care, other social services
Education	Schools, universities, libraries
Financial services	Banking, insurance
Entertainment / recreation	Music industry, tourism, gastronomy
Other	Consulting, brokerage, planning

[1)] District heating and cable TV are based on physical networks but were not considered to be of fundamental importance, which is why they are not listed in Table 1.

Table 3: Key characteristics of selected network sectors (educated guess)

	Electricity supply	Gas supply	Water supply	Sanitation	Railway transport	Road transport[1)]	Telecom-munication
Asset durability	2	2	3	3	2	3	2
Capital intensity	3	2	3	3	2	3	2
Regulation intensity	2	2	3	3	2	2	2
Systemness	3	2	2	2	3	1	3
Public organizations	2	2	3	3	3	3	1
Competition intensity	2	1	0	0	0	0	3
Negative environ-mental impacts	3	2	1	0[2)]	1	1	0

3: very high; 2: high; 1: medium; 0: low

[1)] Provision and ownership of road infrastructure (does not include transportation services)

[2)] In the case of waste water treatment, a key element of the service is to clean polluted water (e.g. by reducing phosphate and nitrate loads, cf. Larsen et al. 2009). However, the sanitation system as a whole uses large amounts of potable water as a means for waste disposal, which is why we classified the net effect as negative.

Interpretation: Asset durability is very high when the life time of physical assets is around five decades or above. It will be classified as high if life time is around two decades. Capital intensity is high if the share of fixed costs is above 60% and high if it is around 30%. Regulation intensity is very high under the circumstances that several aspects including service price, quality, grid access, safety and environmental issues are regulated. It is high when many issues are regulated but not service price. It is low when primarily competition (anti-trust) regulation is relevant in a sector. Systemness is high if technological, institutional and organizational issues are closely intertwined and critical functions exist. The degree of public organizations is very high when most or all suppliers are public utilities and it is low when public organizations play no role in a sector. If there are multiple suppliers to choose from and customers actively compare prices and switch then competition intensity will be very high i. It is low in regulated monopolies. Negative environmental impacts are high when the related costs make up a significant share of the overall service costs.

Table 4: Sector classification

		Capital intensity & Asset durability	
		high	low
Share of public organizations & Intensity of regulation	high	Infrastructure sectors (e.g. electricity supply, water supply, sanitation)	Other public service sectors (e.g. health care, schools and universities, police)
	low	Other capital intensive sectors (e.g. oil supply, air transport, sea transport)	'Conventional' service sectors (e.g. financing, consulting, entertainment)