2 Transformation and Innovation in Power Systems

The electricity system has been innovating itself from the beginning onwards – albeit with a long period of stabilization and incremental growth in between. It is with upcoming crises and impulses from inside and outside that the incumbent system is challenged and that marginal and innovative options (such as renewable technologies, or Combined Cycle Gas Turbines) have made their way into the system up to now. In this chapter, we provide a brief sketch of the transformation process in electricity systems as a context of our more focused case studies. We outline the development of electricity systems in the last one and a half centuries, look at the related innovation cycles and the outcome in terms of the current electricity system.

2.1 Systems in Flux: An Everlasting Path of Electricity Innovation

Today's electricity system is the result of more than 100 years of innovation in progression. In the early days of electricity generation at the beginning of the nineteenth century, electricity was produced by steam engines, fuelled with coal. At first, electricity was only used for a few industrial purposes and for the lighting of public streets and buildings. In Germany, electric light started to enter private households between 1900 and 1910. The process was rather one of supply push than demand pull: Electricity utilities provided customers with free electric lamps and installations and with subsidized tariffs, especially for industry, in order to create connections and increase demand. Early micro grids were linked up with other isles of electricity generation and supply. Later on, large companies protected by government built up the eventual grid architecture dominated by large power stations and the long-distance transport of electricity. Eventually, by 1920, electricity replaced steam as the major source of motive power in industry, and in 1929, electric motors represented 78% of total capacity for driving machines (Ruttan 2001).

On the demand side, the corresponding trend was an ever increasing demand through a variety of novel appliances and applications, a trend that was actively promoted by the electricity supply industry. One important building block of demand was industry motors, another the electrification of railways. In private households, innovations like electric razors, refrigerators, and vacuum cleaners had been promoted since the 1920s. The use of electricity for cooking and heating purposes was heavily advanced from 1925 onwards, and until the end of the 1950s, electric stoves, refrigerators, water heaters and washing machines had arrived in most households (Zängl 1989). The electrical age had arrived.

Since the early twentieth century, the dominating patterns of electricity generation and supply, made up of centralized power plants of an increasing size, did not change in principle until the second half of the twentieth century (Ruttan 2001). The standard boiler-turbogenerator process was only developed with respect to its scale and improved in terms of thermal efficiency. New advances in material research allowed for shifts towards higher temperatures and to reheat cycles in the period of 1948–1957, and higher pressure until the late 1960s. R&D activities have focused on so-called supercritical high temperature thermal processes, with the aim of reaching efficiencies of more than 50% and steam temperatures of up to 700°C, for which new special metals are required. Fig. 2.1 visualizes the

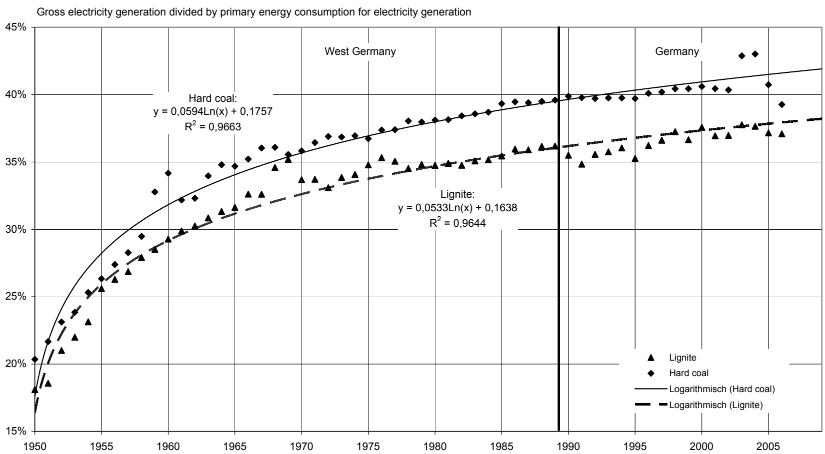

Fig. 2.1 Development of average electrical generation efficiencies in Germany (VIK 1991; AGEB 2007a, b). The vertical line in 1990 marks German reunification, which is the reason for the temporary drop of average lignite efficiencies in Germany

continuous increase of average electrical generation efficiencies in West Germany between 1950 and the mid-1970s. Since then, it has remained more or less constant, with hard coal technologies continuously showing higher efficiencies than lignite. Since the level of 40% electrical efficiency was approached, technical and economic barriers hindered further advances in efficiency. To date, the coal and lignite industry has been making major efforts to improve the generation efficiency of their central power plants, targeting at supercritical thermal processes.

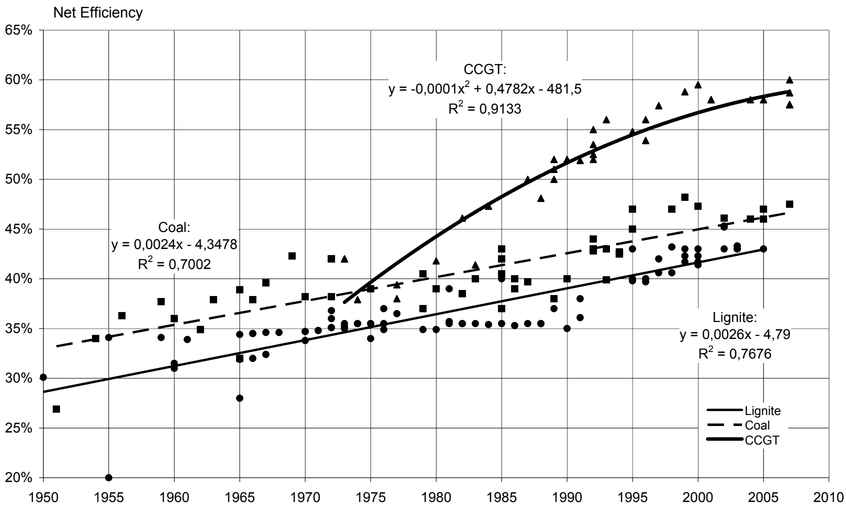

Fig. 2.2 Development of generation efficiency of new thermal power plants (authors' own compilation)

The numbers in Fig. 2.1 reflect the efficiency of the *average* mix of existing coal and lignite power plants respectively. Figure 2.2 provides an idea of the state of the art of *new* power plant efficiency, which is some 5% points above the average existing mix of plants. The figure also shows the impressive increase in generation efficiencies of gas-based power generation, which have recently reached almost 60%. Gas turbines are innovative to the electricity sector, as they only entered the market in the 1990s when combined cycle gas turbines (CCGT) became commercially available. Box 2.1 discusses the usefulness of other innovation indicators to understand innovation dynamics.

Box 2.1 What can we learn from innovation indicators?

Typical innovation indicators are R&D resource inputs, the number of patents granted to a firm, patent applications, and bibliometric data on patterns of scientific publication and citations, in which the data stem from surveys, company accounts and intellectual property rights statistics. Simple input and output indicators, however, have restricted explanatory power. R&D expenses measure the input into innovation, but not the outcome. Patents do not say much about the actual deployment or diffusion of an innovation, and even less about non-technological innovations. And bibliometric analyses of publications on research outcomes do not say much about innovation dynamics and outcomes either. All of these indicators tend to overemphasize invention of new scientific or technical principles as the point of departure of a linear innovation process (Smith 2001). Moreover, they are indicators for product or process innovations with a technical focus rather than for other forms of innovation, such as organizational or policy innovations, consumer-side advances and the like.

More recent conceptual and empirical approaches also try to capture the environment for technical innovations, both inside a company (environmental management systems, changes in corporate strategy, advanced management techniques, new marketing strategies) and with regard to its environment (quality of educational systems, university-industry collaborations, or availability of venture capital). Other indicators include market research related to new product development, and capital investment related to, for example, new product development. The methodological and empirical problems associated with quantifying such indicators and forming composite indicators form the subject of numerous research projects on innovation indicators, and surveys such as the European Innovation Monitoring Initiative, the European Innovation Scoreboard, or the Community Innovation Survey (CIS) – both under the auspices of the European Commission, just as the most recent initiative "Pro-Inno Europe" (www.proinno-europe.eu). The results of CIS, for example, demonstrate that R&D is but one component of innovation expenditures, and by no means the largest (Smith 2001).

Innovation, however, has also taken place on the demand side. Unfortunately, things are even more complex in this regard, and useful indicators are hard to define. For example, some indication of innovation could be drawn from market penetration rates of efficient appliances, such as efficient refrigerators or washing machines. Here, however, a major problem on the consumer side becomes apparent: Not every innovation is sustainable as it may create new electricity consumption. Also, besides market penetration rates of efficient appliances, indicators for measuring innovative behavior are difficult to define and identify. Similarly, the assessment of indicators for institutional, policy and other societal innovation denotes a considerable research challenge with a questionable outcome. In all of these cases, it seems more fruitful to take an in-depth look at the evolution dynamics of exemplary innovations such as emissions trading in the case of an innovative energy and climate policy tool, and network regulation in the case of governing the electricity grid.

One single major innovation – which fitted well into the prevailing system architecture – was the development of nuclear energy from the 1950s onwards. The first nuclear power plant started operating in 1961. The vision emerged that nuclear energy could be the solution to any energy supply problem. Yet the economics of scale and related cost reductions were not realized as anticipated, and the technology needed to be bolstered by massive subsidies from government and financing institutions. Also, due to the related nuclear risks for society, nuclear energy triggered massive political conflicts from the mid-1970s onwards.

2.2 Are we Locked in a Carbon (and Nuclear) Trap?

Innovation depends on previous historical development steps. Many improvements in efficiencies are based on advances in materials and other technological or organizational elements. Thus, innovation is, among other factors, also a result of experience.

From the beginning onwards, increasing economics of scale seemed to be a natural law in electricity generation. Belief in the advantages of ever-larger power stations integrated in the electricity network, dominated the perception and institutional design of the electricity system until the 1980s. Consequently, most electricity systems worldwide were completely protected from competition. Highly concentrated markets of state-owned monopolies, public–private partnerships or private companies were established and protected, all in similar ways. In Germany, for example, the Federal Energy Management Act of 1935 set the seal on this structure for more than 60 years – until its revision in 1998.

The related phenomenon of decreasing specific investment costs for ever-larger electricity generating technologies and companies, and the consequences of learning and experience for technology choice, have been extensively investigated in the last few decades, both theoretically and empirically. Learning is a cumulative process on both the level of the firm and of the sector (or industry, or country). It is a phenomenon that benefits society, but that also contributes to explaining the existence of path dependencies and lock-in, for example in a carbon (and nuclear) based electricity system. Therefore the question is: What role does learning then play in explaining the current system structure, and what does that mean for the future development and innovation opportunities? Does it mean that the likelihood to switch to a more sustainable low carbon society is smallest?

In his theoretical assessment of competition between alternative technologies, Arthur (1989) prepared the theoretical ground for this phenomenon by highlighting the incidence of increasing returns to adoption (IRA), or falling specific cost of technology deployment. Arthur (1989) proposes a positive feedback between adoption and competitiveness. The more a technology is adopted, the more likely it is to be further adopted. This is due to increasing returns to adoption, which in turn can be traced back to four factors: scale economies (declining unit costs), learning effects (experience, learning by doing), adaptive expectations (adoption reduces uncertainty), and network economics (the more users, the more useful a technology is). Together with other driving factors such as R&D, knowledge spillovers, and exogenous market dynamics, cumulative learning or experience is a major factor for IRA (Ibenholt 2002; Nemet 2006; Papineau 2006). As a consequence, once a technology has gained an advance compared to alternatives, this leads to self-reinforcing and self-stabilizing dynamics of technology adaptation. In short, these dynamics may lead to path dependencies and even to a situation of technological lock-in, as has been shown by David (1985) for the QUERTY keyboard design, and by Cowan (1990) for the light water nuclear reactor in the case of the electricity system. As a matter of fact, power generation in Germany in the early twenty-first century is still dominated by large scale coal, lignite and nuclear power plants, which is also an example of system lock-in (Unruh 2000, 2002; Unruh and Carrillo-Hermosilla 2006).

Another indicator for the dominant technology choice and priorities on national and international levels can be found in the composition of R&D expenses. Table 2.1 demonstrates the major strategic relevance still allocated to research in both nuclear fission and fusion. Considerably more research funds are flowing into these technologies than into future ones such as small-scale renewable technologies. But the numbers also show the increasing relevance of alternatives: Renewable energy sources, for example, enjoy a rising share, amounting to 24% in 2005. Research in energy efficiency, by comparison, has been neglected ever since. Yet these numbers already indicate that path dependency does not necessarily lead to an everlasting carbon lock-in.

In fact, the prevailing paradigm of ever increasing sizes of power generation slowly became obsolete in the 1980s. The case of conventional steam turbine power plants shows that learning rates can decrease or even stagnate over time (Helden and Muysken 1983). At around the same time, the dominating setting of large generation plants increasingly became complemented by smaller and more distributed technologies. Combined Cycle Gas Turbines (CCGT), for example, allowed for smaller investment capital needs (and thus risks), shorter building periods and higher flexibility in reacting to fluctuations in electricity demand, as they can more easily

Table 2.1 Composition of German federal R&D costs regarding energy (IEA 2007)

	1995		2000		2005	
	Mill €	%	Mill €	%	Mill €	%
Energy efficiency	15.2	3.6	9.5	2.3	19.6	4.7
Fossil fuels	13.6	3.3	9.6	2.4	11.5	2.8
Renewable energy sources of which	74.9	17.9	76.9	19.0	99.4	24.1
– Photovoltaics	31.5	7.5	38.9	9.6	41.0	9.9
– Solar thermal power	3.5	0.8	1.5	0.4	5.0	1.2
Nuclear fission and fusion	166.7	39.9	153.0	37.7	137.2	33.2
Hydrogen and fuel cells of which	–	n.a.	–	n.a.	21.5	5.2
– Stationary fuel cells	–	n.a.	–	n.a.	19.3	4.7
Other power and storage technologies	0.0	0.0	22.1	5.4	3.3	0.8
Total other R&D	12.8	3.1	11.5	2.8	120.6	29.2
Total Energy R&D	417.4	100.0	405.8	100.0	413.2	100.0

adapt their output. Also, renewable energies gained increasing attention from politicians and, as a result of advantageous framework conditions, also a rising share of electricity generation. In consequence, continuous learning effects were reported for most renewable energy technologies, allowing for a sustained decrease in generation costs (except for fuel-based systems such as biomass).

Impressive examples of the decline in cost with increasing cumulative production of innovative technologies are renewable energies such as wind and photovoltaic. In a recent survey, the IEA (2006) reports learning rates[1] of between 4 and 8% for the production of wind turbines in Denmark and Germany, with slightly higher rates for the complete process including installation. For PV modules, the decrease in price has been steady for more than three decades now, with a learning rate of about 20%. Nevertheless, PV is still not competitive.

Germany is a good example when studying the effects of public support for an innovation on deployment numbers in the case of renewable energy. Guaranteed feed-in tariffs and other subsidies have attracted investment capital for production sites in Germany. As a result of these incentives, electricity generation from renewable energies more than doubled between

[1] A learning rate of 10% reflects a 10% cost reduction with each doubling of installed capacity.

1999 and 2006 (from 30.5 to 70.4 TWh). This was mostly accounted for by hydro- and wind power, despite the growing number of small-scale installations. The cumulative capacity of PV cells, for example, grew from 2 MW in 1990 to 2,740 MW in 2006, but PV still accounted for only 0.4% of total electricity generation, or 2,220 GWh, in 2006 (Fig. 2.3). And despite its geographical and climatical disadvantages, Germany ranks among the leading countries in the world in terms of both the construction and use of solar cells (modules) and wind turbines. Also, distribution and marketing structures are well developed, with numerous information sites and services, and large amounts being continuously invested in new production sites.

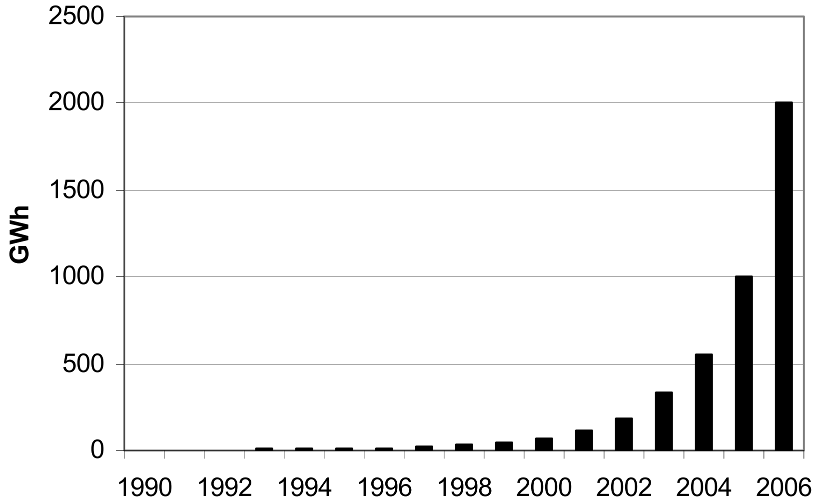

Fig. 2.3 Electricity generation from PV in Germany, 1990–2006 (BMU 2007)

New technologies can also begin their market penetration in a process of hybridization, that is, starting from a rather complementary relationship of established and new technologies. In the UK, for example, CCGT developed its potential in such a process of hybridization with incumbent technologies, first offering peak load capacities and then taking over due to its economic advantages, as its only economic risk was (and is) the gas price (Islas 1997). The technology led to a "dash for gas" (Winskel 2002), increasing its share from 0 to some 30% of generation capacity within a decade and changing the structure of electricity supply substantially. Also, despite the increase in gas prices, 33.5% of total generation in the UK still stems from CCGT in 2006 (BERR 2007).

Thus, change is indeed happening, and alternative technologies are entering the scene. These rather optimistic examples, however, should not distract from the fact that the incumbent system of fossil fired and nuclear plants is still dominating the supply side of the electricity system, which supports the idea of inertia in large technological systems. In many cases, such as renewable technologies and CCGT, the technology or idea as such already existed for a while before it was able to enter a broader market. The question therefore arises as to what exactly pushed them into broader deployment.

2.3 Current Stimuli for Change

Major impulses for change in the dominating system design can be expected to arise from frictions or bottlenecks in the existing architecture of such large technological systems. Such "reverse salients", as Hughes (1983) calls them, form a limitation to the development of the system. Substantial or disruptive challenges to an everlasting linear development of the system could originate from, for example, technological or demand-side factors, or from changes in the external setting.

Two major changes on the macro-level became relevant for the electricity sector in the 1990s: market liberalization on the one hand, and the international climate protection regime on the other hand. Both macro-processes – liberalization and climate change concerns – add to the enduring impulse stemming from the oil crises of the 1970s, which raised awareness of supply security and resource depletion issues. These macro-level events are both accompanied and accommodated by a third component, which are technological developments that are relevant to the electricity sector.

2.3.1 Impacts of Liberalization

In the 1990s, a spate of liberalization processes made their way across Europe and the rest of the world, changing the institutional setting for electricity generation and consumption. While the designs differ substantially with the country contexts, the underlying economic paradigm is the same: After decades of protected monopolies, based on an understanding of the vertically integrated electricity system as a "natural monopoly", competition on the generation and distribution levels are now expected to create more choice, more diverse supplier structures, and thus less expensive electricity for consumers. Germany formally liberalized its electricity sector in April 1998 on all levels, including final customers, in one fell swoop. Box 2.2 provides an overview of today's electricity system in Germany.

Box 2.2 Structural characteristics of the German electricity system

The German electricity system is carbon intensive, with coal and lignite as major inputs into generation; 43% of German CO_2 emissions are related to electricity overwhelmingly generated in large fossil fired plants. Germany has committed itself to a CO_2 reduction of 40% by 2020 compared to 2005 levels. Stringent policy targets for renewable energies and an accommodating Renewable Energy Sources Act are one means to reach this target; others are efficiency improvements and clean coal technologies as well as – recently – the development of CCS.

Electricity reform in Germany took place in several steps. In April 1998, full competition on all levels was introduced in the formerly protected market. In 2005, an electricity regulator was installed to formulate and implement an incentive based regulation of grid access and grid use. Legal unbundling of generation, transmission and distribution/sales activities was compulsory by 1 July 2007.

The development of key indicators for the state of competition is disappointing. Prior to liberalization, the electricity system consisted of about 900 local utilities, some 60 regional distributors and about nine large generation and transmission companies. Now a wave of major mergers reduced the number of large players to four, E.ON, RWE, Vattenfall, and Energie Baden-Württemberg (EnBW), plus some large municipalities and regional suppliers. The big four own the long-distance electricity grid. In 2006, E.ON and RWE supplied 53%, and all big four together supplied 80% of total electricity generated in Germany; they have at their disposal 286 shareholdings (>10%) in regional and local utilities (Monopolkommission 2007). Both horizontal and vertical concentration increased after liberalization (Brunekreeft and Twelemann 2005; Öko-Institut 2005; London Economics 2007). Investigations into factual market power based on the Lerner Index[2] estimated a mark-up on marginal cost pricing of about 20% for 2005 (Hirschhausen et al. 2007; Zimmer et al. 2007). One reason is the poor regulation of network access after liberalization. Grid access was initially organized by self-regulation (so-called "negotiated grid access"), which was an effective means of restraining competition and newcomers. In 2005, motivated by an intervention by the European Commission, an independent regulator (Bundesnetzagentur, Federal Network Agency) was established, which went on to implement an incentive oriented regulation.

On the consumer side, despite increasing debate about exaggerated electricity price rises, the supplier change rate of household electricity customers is much below those in, for example, the UK. Depending on the data source, 7–12% changed their supplier, with an increasing trend. The numbers are higher in the case of commercial customers. Also, independent power producers, energy traders, Third Party Financing institutions and the like started entering the markets in 1998. However, the number of newcomers decreased again after 2000.

---

[2] The Lerner Index relates the difference between market prices and marginal cost to the market price. It has a value between 0 and 1, where 0 indicates that no market power is exercised.

In the real world context, the outcome of the different liberalization experiments worldwide has been mostly disillusioning to date. In his review of liberalization processes and results, Thomas (2006) lists a large number of failures and deviations from the competitive model when re-regulation is introduced in order to balance the desire for a secure and reliable electricity system with the investment risks related to competitive markets, or network access for newcomers in vertically integrated systems as in Germany. Thomas concludes that "all that is left of the competitive element of the model is the free market rhetoric" (Thomas 2006). There are several signs underlining this pessimistic perception: electricity prices are as high as they used to be under monopoly conditions; market actors now play oligopoly or duopoly rather than a free competition game; and vertical integration is still pervasive. Yet investment is indeed more risk related than it used to be under monopoly conditions, and with liberalization, this risk has been increasing.

With regard to innovation, market liberalization can be expected to transform the selection environment for search and innovation decisions and changes, and may thereby weaken prevailing technological regimes (Markard and Truffer 2006). This is due to two effects: First, new market entrants may pursue new technology paths and thus cause technological competition, and second, competition theoretically also creates a need for more diversified, trendy products and services offered on the market in order to survive in competition, as is the case with many goods and services. It thus has the potential to increase innovation activities and variation on the firm level. On the other hand, competitive pressures may also reduce the efforts to risky and costly innovation.

Pollitt and Jamasb (2005) review a broad body of literature on the effects of deregulation, unbundling, privatization and general restructuring of electricity systems on innovation and find that they are linked to a significant decline in R&D expenses, while R&D productivity increased with electricity reforms. Among the factors responsible for the decrease are smaller firm sizes, organizational diseconomies of vertical disintegration, and a decreasing propensity of private firms to take risks in an environment of increased uncertainty and a competitive market environment. On the other hand, a price cap regulation tends to increase technical progress, at least compared to rate of return regulation.

Despite this rather pessimistic account, a number of indirect innovation incentives can be observed and related to national electricity market reforms, and at the same time show the differences between countries. One example is the generous provisions for cogeneration plants in Germany, which are unique in Europe. Germany introduced a bonus for electricity from cogeneration in order to protect it from too much competition. Another example is the rise of CCGT in the UK which is also a result of liberalization, which sees newcomers succeeding on the market with an innovative technology. In Germany, by comparison, structural dynamics and the coalition of actors in coal mining and coal-based electricity generation were powerful in holding back CCGT, namely in the conflict relating to the taxation of gas for power generation. Neither coal nor lignite has ever been subject to input taxation, but in the case of gas, such taxes existed and were relieved only for highly efficient plants. The underlying political negotiation process created considerable uncertainty for investors and thus troubled the early CCGT investors (Stadthaus 2001). In both countries, CCGT has suffered from high gas prices since 2005, which caused the window of economic opportunit ies for CCGT to be closed again.

2.3.2 Increasing Climate Change Concerns

Parallel to market liberalization, a second major – or macro – impact developed momentum: societal awareness of the risks of climate change increased continuously and thus also started impacting on the course and focus of innovation activities. Concerns about the environment are raising new heights with the upcoming awareness of human-made climate change.

Up to now the increasing concern about the climate and the environment has led to a number of institutional innovations and a changing framework for technological and organizational innovations. A whole new business stream for environmental improvements developed. Building on the impulses from the oil shocks in the 1970s, an intense debate about the future of our energy supply started in the 1990s. Environmental concerns activated the use of more or less the whole environmental policy toolbox, with all possible instruments seeing their realization in one form or another: Ecological taxes and voluntary agreements, efficiency labeling, labeling of electricity, "green" electricity, funding of R&D in new technologies, emissions trading, feed-in remunerations for renewable energies and cogeneration, and all forms of market information and introduction programs and so forth were introduced. Governments set themselves targets for renewable technologies and for efficiency. This gave a major impulse for renewable energies and energy efficiency, and is likely to continue doing so, inspiring innovative actors to become dynamic innovators.

The United Nations Framework Convention on Climate Change (UNFCCC) and its 1997 Kyoto Protocol formed the first international institutional framework for global climate change mitigation. International reports, such as the four IPCC assessment reports as well as a number of national reports (e.g. the Stern report on the economics of climate change) raised awareness and called for immediate action. The 2005 implementation of an EU-wide emissions trading system is a direct offspring of this process. The main impact of the EU ETS is to give CO_2 emissions a price, thereby altering the setting for investment decisions. This, in turn, is a premise for technological innovations such as distributed generation or CCS. With the continuous growth of global emissions and growing concerns about global climate change, the European Union initiated a number of processes to keep the global temperature increase below 2°C. These include specific mid-term targets for emissions reductions, renewable energy shares, biofuels, and improvements in energy efficiency. An integrated energy and climate program, including a directive for the continuation of the EU ETS, for renewable energy, for CCS etc., is under development to ensure that these targets will be fulfilled. Similarly, the German government initiated an integrated energy and climate policy package to ensure that these targets and additional more stringent national targets are met.

In the field of energy efficiency, the EU directive on energy efficiency and energy services (Directive 2006/32/EC) has been a major policy initiative. It is currently triggering, among other things, innovations in consumer feedback on their electricity consumption via improved electricity bills and other means.

In the wake of these developments, interest in renewable energy sources and energy efficiency grew. “New” renewable energies beyond the established hydropower started developing momentum in terms of technological development, learning curves and related cost reduction, and market penetration. Supported by governmental programs and legislation, they entered into commercial electricity generation, albeit with different shares in total electricity supply in different countries, depending on the respective form and level of support. In Germany, for example, renewable energy took off with the Federal Feed-in Law in 1990 and even more with the Federal Renewable Energy Sources Act of 2000, which guarantees operators of renewable electricity generation technologies preferential treatment for their electricity feed-in as well as a fixed feed-in remuneration for usually 20 years. The share of renewable technologies rose to around 14% by the end of 2007 (BMU 2007), and Germany now ranks among the leading innovator and producer countries in the world in terms of the development and construction of solar cells (modules) and wind turbines.

2.3.3 Impulses from Technological Change

A third major factor impacting on transition processes in the electricity sector is technological change. New technological developments can be specific to the electricity sector, such as new or improved power generation technologies. They can also be of a rather generic type (e.g. information and communication technologies (ICT)) or progress in materials research and other fundamental science. Generic technological advances are flexible in their deployment and may, for example, enable improvements in generation and related technologies (such as high temperature conventional coal or gas plants) or increase the options available for consumer feedback (e.g. via *smart metering*, or *smart houses*).

Technological change can interact with and even stimulate institutional change and influence the societal setting for innovation (Werle 2003; Rohracher 2007; Dolata and Werle 2007). In particular, modern ICT can be considered a prerequisite or even be core to stimulating regulatory and organizational reform in the electricity system. The operation of electricity exchanges, for example, is unimaginable without ICT. Liberalization of the electricity markets, in particular the unbundling of electricity generation, transport and distribution, and the implementation of electricity exchanges, presumes the existence of technological solutions for handling the enormous amount of information involved – which again is unthinkable without ICT. In fact, the universal character and impact of ICT can even be interpreted as a change in the ruling techno-economic paradigm (Freeman and Perez 1988; Dolata 2007), which – in the case of electricity – has the possible (or even unavoidable) consequence of major amendments in the institutional and technical architecture of the system.

Similarly, the discovery and development of new material allows for better and more efficient generation and transmission technologies. The commercial development of inventions – such as the fuel cell or small-scale Stirling motors, renewable technologies as well as the development of more efficient fossil-based power plants (with or without integrated carbon capture) – is based on and entails further advancements in materials and mechanics.

Technological change also has the potential of triggering change in the current generation structure of the electricity system. An example is the interplay of new technological developments on the level of generation. After decades of increasing returns to scale (with the result of ever increasing sizes of power stations), new generation technologies are rather smaller scaled or even of a distributed nature, such as small or micro cogeneration units and small or medium-size renewable energies. These technologies are often fluctuating in their provision of electricity to the grid and – so far – need to be balanced by other, quickly and permanently available, generation technologies. In this context, new technology developments and ICT solutions are important for integrating such sustainable technologies into a reliable overall electricity system.

It was also with liberalization in the 1990s that a comparatively new and highly efficient generation technology managed to spread successfully into the market and disarrange the incumbent system of large-scale electric power plants. The combined cycle gas turbine (CCGT), fired with natural gas, allowed electrical efficiencies of 56% and more to be reached, coupled with much lower investment costs of about 450–550€/kW, compared to 1,100–1,300€/kW for lignite or coal plants (Erdmann and Zweifel 2008). In the absence of advanced electricity storage technology, CCGT offered the "missing link" to fluctuating energy generation technologies. However, despite its comparatively low specific investment costs and its high efficiency, CCGT suffered more and more from increasing prices for natural gas. Its competitive advantage now lies in the peak load segment of electricity generation. In consequence, after an initial "dash for gas" (Winskel 2002) in the UK in the 1990s, followed by announcements of increasing numbers of CCGT in Germany, the number of actually commissioned and newly planned gas plants decreased in Germany, and also in the UK.

Interestingly, in the UK, the advantages of CCGT were not attractive to the incumbent actors; it was newcomers to the market who realized its enormous potential in a mix of coincidence and contingence (Winskel 2002: 585). This highlights the role of both liberalization as a setting to change, and of actors taking their chances in such a changing environment, in successful transition processes – an aspect to which we shall now turn.

2.4 Actors and Institutions of Change

All of the above "macro" impact factors are interlinked. Also, the coevolution of technological advancements and institutional change as stipulated by Hughes (1987) or Nelson (1994), and its relevance to sector transitions, are already at hand. Transition, moreover, needs action, and the role of actors and actor networks in realizing possible changes deserves more attention than it receives in many cases.

The institutional setting forms a framework for innovation, but is also subject to change and innovation itself. It is both external and internal to the electricity system and its components. It consists of the regulation and administration of grid access, standards and technical norms, plus the setting of political regulation such as feed-in remuneration, priority grid access, policy instruments such as ecological taxes or emissions trading, and fiscal law, for example with respect to energy taxes and exemptions or subsidies in general. In addition, new institutions like power exchanges or independent system operators (in, for example, the UK but not in Germany) are also relevant framework factors. Institutions impact on the administrative, technological and economic feasibility and viability of innovations and their implementation.

It seems superfluous to point to the fact that actors are core to any change, be it of institutions or by introducing new artifacts to the electricity system. Actors are responsible for inventing and for spreading novelties. Actors are equally accountable for blocking unwanted innovation. What is more, actors tend to form networks, and networks are usually more powerful and more successful in pushing their ideas through than individual actors. They are even stronger when they manage to integrate complementary or even competing forces such as research actors, politicians and industrial stakeholders. In the case of innovation policy and politics, this insight led to governmental support for the formation of knowledge networks, as can be found in the fields of renewable energy and CCS, for example. Also, ministerial or interministerial "working groups" on energy legislation and policy formulation, with invitees from industry, NGOs and inputs from the research community, are a popular means to advance innovation and innovation policy.

The system of actors in electricity and innovation is complex to grasp and varies, depending on the specific innovation. It includes the whole product and process chain, starting from the manufacturers of generation and transmission technologies, the electricity utilities themselves, the appliance and engineering equipment industry, and eventually the commercial, industrial and household consumers. These actors are surrounded by regulating and stimulating institutional and policy actors, and by a research community as diverse in their focus and interest as the other different elements of this large technological system. Also, many of the concrete impulses for changes on the national level stem from international sources and the European Commission, a prominent example being the EU ETS or CCS. All in all, there are multiple forms of potential linkages and networks and their innovation impacts; assessments of the respective sub-networks or settings of actors will be presented in the innovation cases that follow.

References

AGEB (2007a) Bruttostromerzeugung in Deutschland von 1990 bis 2006 nach Energieträgern. Arbeitsgemeinschaft Energiebilanzen, Berlin

AGEB (2007b) Einsatz von Energieträgern zur Stromerzeugung in Deutschland. Arbeitsgemeinschaft Energiebilanzen, Berlin

Arthur WB (1989) Competing technologies, increasing returns, and lock-in by historical events. The Economic Journal 99 (394): 116–131

BERR (2007) Digest of United Kingdom energy statistics 2007. Retrieved 21 January 2008, from http://www.berr.gov.uk/
BMU (2007) Erneuerbare Energien in Zahlen – nationale und internationale Entwicklung. Stand: November 2007. Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, Berlin
Brunekreeft G, Twelemann S (2005) Regulating the electricity supply industry in Germany. The Energy Journal 26 (Special Issue: European Electricity Liberalisation): 99–126
Cowan R (1990) Nuclear power reactors: a study in technological lock-in. Journal of Economic History 50 (3): 541–567
David PA (1985) Clio and the economics of QWERTY. American Economic Review 75 (2): 332–337
Dolata U (2007) Technik und sektoraler Wandel. Technologische Eingriffstiefe, sektorale Adaptionsfähigkeit und soziotechnische Transformationsmuster. Discussion Paper 07/3. Max-Planck-Institut für Gesellschaftsforschung Köln, 2008/01/22
Dolata U, Werle R (eds) (2007) Gesellschaft und die Macht der Technik: Sozioökonomischer und institutioneller Wandel durch Technisierung, Campus, Frankfurt
Erdmann G, Zweifel P (2008) Energieökonomik. Theorie und Anwendungen. Springer, Berlin
Freeman C, Perez C (1988) Structural crisis of adjustment, business cycles and investment behaviour. In: Dosi G, Freeman C, Nelson R, Silverberg G, Soete L (eds) Technical change and economic theory. Pinter, London, pp 38–66
Helden GJv, Muysken J (1983) Diseconomies of scale for plant utilisation in electricity generation. Economics Letters 11 (3): 285–289
Hirschhausen Cv, Weigt H, Zachmann G (2007) Preisbildung und Marktmacht auf den Elektrizitätsmärkten in Deutschland. Grundlegende Mechanismen und empirische Evidenz. im Auftrag des VIK, Dresden
Hughes TP (1983) Networks of Power: Electrification in Western Society 1880-1930. The Johns Hopkins University Press, Baltimore
Hughes TP (1987) The evolution of large technological systems. In: Bijker WE, Hughes TP, Pinch T (eds) The social construction of technological systems. The MIT Press, Cambridge, MA, pp 51–82
Ibenholt K (2002) Explaining learning curves for wind power. Energy Policy 30 (13): 1181–1189
IEA (2006) Energy technology perspectives. OECD/IEA (International Energy Agency), Paris
IEA (2007) IEA Energy Technology R&D Database Edition - Database Tables RDD Budgets, Vol 2007 release 01. Retrieved 2 June 2008, from http://oberon.souceoecd.org/vl=6972643/cl=26/ini=rcse/nw=1/rpsv/ij/oecdstats/17266564/v355n1/s1/p1
Islas J (1997) Getting round the lock-in in electricity generating systems: the example of the gas turbine. Research Policy 26 (1): 49–66

London Economics (2007) Structure and Performance of Six European Wholesale Electricity Markets in 2003, 2004 and 2005, Part II: Results for Germany and Spain, London
Markard J, Truffer B (2006) Innovation processes in large technical systems: market liberalization as a driver for radical changes? Research Policy 35 (5): 609–625
Monopolkommission (2007) Strom und Gas 2007 – Wettbewerbsdefizite und zögerliche Regulierung. Sondergutachten 49, Berlin/Bonn
Nelson R (1994) The co-evolution of technology, industrial structure and supporting institutions. Industrial and Corporate Change 3 (1): 47–63
Nemet GF (2006) Beyond the learning curve: factors influencing cost reductions in photovoltaics. Energy Policy 34: 3218–3232
Öko-Institut (2005) Power generation market concentration in europe 1996–2004. An empirical analysis, Berlin
Papineau M (2006) An economic perspective on experience curves and dynamic economies in renewable energy technologies. Energy Policy 34: 422–432
Pollitt M, Jamasb T (2005) Deregulation and R&D in network industries: the case of the electricity industry. Cambridge Working Papers in Economics 0533. University of Cambridge, Cambridge, UK
Rohracher H (2007) Die Wechselwirkung technischen und institutionellen Wandels in der Transformation von Energiesystemen. In: Dolata U, Werle R (eds) Gesellschaft und die Macht der Technik: Sozioökonomischer und institutioneller Wandel durch Technisierung. Max-Planck Institut für Gesellschaftsforschung, Köln, pp 133–51
Ruttan VW (2001) Technology, growth, and development. An induced innovation perspective. Oxford University Press, New York
Smith K (2001) Innovation indicators and the knowledge economy: concepts, results and policy challenges. In: Thuriaux B, Arnold E, Couchot C (eds) Innovation and enterprise creation: statistics and indicators, Proceedings, 23–24 Nov 2000, Sophia Antipolis, France. European Commission, DG Enterprise, Brussels, pp 14–24
Stadthaus M (2001) Der Konflikt um moderne Gaskraftwerke (GuD) im Rahmen der ökologischen Steuerreform. FFU-report 01-03, Forschungsstelle für Umweltpolitik, Berlin
Thomas S (2006) The grin of the Cheshire cat. Energy Policy 34 (15): 974–1983
Unruh GC (2000) Understanding carbon lock-in. Energy Policy 28 (12): 817–830
Unruh GC (2002) Escaping carbon lock-in. Energy Policy, 30 (4): 317–325
Unruh GC, Carrillo-Hermosilla J (2006) Globalizing carbon lock-in. Energy Policy 34 (10): 1185–1197
VIK (ed) (1991) Statistik der Energiewirtschaft, Verband der Industriellen Energie- und Kraftwirtschaft e.V., Essen
Werle R (2003) Institutionalistische Technikanalyse: Stand und Perspektiven. Discussion Paper 03/8. Max-Planck Institut für Gesellschaftsforschung, Köln
Winskel M (2002) When systems are overthrown: the ‘dash for gas’ in the British electricity supply industry. Social Studies of Science 32: 563–598

Zängl W (1989) Deutschlands Strom. Die Politik der Elektrifizierung von 1866 bis heute. Campus, Frankfurt/New York

Zimmer M, Lang C, Schwarz H-G (2007) Marktstruktur und Konzentration in der deutschen Stromerzeugung 2006. Zeitschrift für Energie, Markt und Wettbewerb 5: 64–69