Evolut Inst Econ Rev (2017) 14:141–169
DOI 10.1007/s40844-016-0066-x

ARTICLE

Energy transition in Germany: a case study on a policy-driven structural change of the energy system

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Published online: 18 January 2017

Abstract The German energy transition ("Energiewende"), i.e., shifting the basis of the energy system from fossil and nuclear fuels to renewable energy constitutes a policy-driven structural change of the energy systems. The fundamental political decisions on nuclear phase-out and the deep decarbonisation of the energy system were based on specific risk considerations in German society, formed by political and learning processes over more than two decades, including the experiences made with the roll-out of renewable energies from 1990 to 2010 that created significant technology optimism in this field. The major challenges for the energy transition do not arise from technological issues or the system costs of a renewables-based system if the once-only investments in innovation are taken into account (that contributed significantly to the massive cost decrease of wind and solar energy at global level). Structural challenges arise first from the dominance of variable renewable energies, which changes generation patterns and shifts cost structures to high shares of capital and low or even zero marginal costs. This triggers the need for restructured power market design that enables price-based system coordination as well as the payback of investments in a low marginal cost environment and re-adjusts the cost allocation among the different consumer groups. Second, the increasing diversity in the power system brings in a broad range of new players and new economic appraisals (self-generation, etc.) that also requires—beyond new dimensions of coordination—structural changes in the regulatory framework. Third, the spatial patterns of the electricity system necessitate large-scale structural changes in the network infrastructures, which demand a sensitive reflection of public acceptance and network regulation approaches. A successful energy transition beyond its present stage requires stringent and holistic policy approaches that are based on four pillars:

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paving the way for clean energy, designing the exit game for the high-carbon assets, triggering the network infrastructures and making innovation work in time.

Keywords Energy transition · Electricity policy · Decarbonisation · Renewable energy · Germany

JEL Classification Q48 · Q42 · Q47 · Q28 · Q38 · N74

1 Introduction

Energy systems are characterized by long-lived capital stocks and significant inertia but have always been dynamic systems. On one hand, they have been endogenously driven by technology and the respective availability of natural resources for energy production. Starting from biomass and hydropower, the energy supply of modern societies shifted first to coal, was complemented by mineral oil and gas and partly by nuclear energy, before modern renewable energy sources like wind and solar reached a level of technology advancement that allowed them to play a more significant role. On the other hand and equally important, the energy sector has been perceived as a strategic sector for most industrialized societies for a long time and as such was always subject to political constraints and drivers. This political framing of the energy sector focuses typically specific primary energy supply structures, e.g., with regard to the use of domestic resources to ensure security of supply or protect domestic industries, but is also relevant for large network infrastructure projects which often have geo-strategic elements. Even if the energy systems changed significantly during the course of the twentieth century, most of these changes occurred as relatively soft changeovers (natural gas or nuclear fuel substituting coal in large steam generation power plants) or the phase-in of completely new segments of the energy system (e.g., the mineral oil-driven motorization based on the internal combustion engine).

In distinction from these kinds of changes, a new type of energy system change becomes visible after the turn from the twentieth to the twenty-first century. It is essentially policy driven, is mainly based on risk considerations and actively addresses an accelerated structural change of the energy system, which is supported by major innovations that are—at least for some important elements (e.g., modern renewable power generation technologies) and at least for the commercialization part of the innovation chain—induced by the efforts of energy policy. In this paper, this new policy approach, termed in different jurisdictions and with different ambition levels as “energy transition”, “transition énergétique” or “Energiewende”, is defined as a policy-driven structural change of the energy system, with the combination of strong policy drivers and the structural dimension of the change forming the constitutive elements of the concept.

Germany is one of the countries that embarked comparatively early on an energy transition policy of this kind, triggered by specific political circumstances in terms of policy awareness and governance structure, but also by its self-conception as an innovation-based economy with a strong focus on system solutions.

This paper tries to summarize some of the lessons learned in the one and a half decades of practical experience gathered with energy transition policies in Germany and to indicate the emerging challenges and potential solutions ahead.

Energy transition is, especially in the framework of deep decarbonization policies, relevant for the whole energy system, including transportation and the industrial, commercial and residential end-use sectors as well as other greenhouse gas emitting sectors (e.g., industrial processes, waste management, and agriculture). This paper addresses, however, exclusively the electricity sector, which is the largest single source of greenhouse gas emissions (40%) in Germany and—due to the electrification option—of strategic importance for other sectors in the context of ambitious climate policies.

2 Political, economic, regulatory and strategic context

German energy policy and even more so German electricity policy is determined and characterized by a series of specific circumstances that have been relatively robust in recent decades, even if the emphasis on specific issues has slightly changed over the course of time:

First, the energy sector is a sector of large strategic and political importance but the value added created by the energy industries constitutes only a 1.5–2% share of gross domestic product in Germany. Even the energy import bill of the energy resource-poor country represents typically a level of GDP around 3%.

Second, the general governance structures as well as the structures of the electricity sector are traditionally characterized by power sharing and significant decentral elements. For most policies, including energy and electricity policy, the complex governance structure of the country with its sensitive power sharing between the federal, the state and the municipal levels requires balanced political and legislative processes, and as a minimum, balanced political and regulatory solutions. Political decision making on highly controversial issues (e.g., nuclear policies) is time-consuming and longer-lasting; legislation that is based on broader public and political consensus (e.g., classic clean air or climate policy) can, however, proceed comparatively quickly. As a result, the governance structures lead to relatively robust, accountable and steady policy pathways; abrupt policy swings are rather rare events in German politics.

Based on the municipalities' constitutional right to maintain public services, the electricity industry is traditionally characterized by a large number of municipal utilities and a significant number of electricity generators. About 900 utilities operate electricity networks; approximately 70 utilities operate generation capacities of more than 100 megawatts; three fourths of the conventional generation capacities are nevertheless owned by four major utilities. Over the course of time, this large variety of entities has enabled a broad range of experiments to be undertaken in business strategies and (local and/or regional) energy policies but also built the grounds for strong competition after the liberalization of the electricity markets in the late 1990s.

Third, it needs to be highlighted that the energy and climate policy of Germany was increasingly embedded in and interacted with, the respective trends and activities of the European Union (EU):

- With regard to the strategic and target level, the European energy and climate package of 2008 (European Commission (EC) 2008) set legally binding targets for greenhouse gas emissions and the use of renewable energy sources as well as indicative targets for energy efficiency. Even if the German national targets were more ambitious, the setting of legally binding targets at EU level stabilized the German target-driven policy approach, especially if the special circumstances of German reunification are taken into account. The longer-term roadmaps for a low-carbon economy (European Commission (EC) 2011a) and the energy roadmap 2050 (European Commission (EC) 2011b) created a more comprehensive strategic framework for energy and climate policies that allows for transparent consistency checks between short- and medium-term policies and long-term goals.
- The liberalization of the electricity and gas market with the three internal market packages of the European Union (1996, 2003, 2009b) constantly faced strong resistance from different German governments in the respective period, which paved the way for at least a slowdown of the structural changes but did not ultimately succeed in blocking them (unbundling of generation, transmission and distribution networks, set-up of energy market regulators). During the further course of the energy transition, key provisions of the market liberalization (vulnerability of the electric utilities to customer choice, increasingly strict unbundling of network, generation and sales activities) and the evolving market structures (liquid wholesale markets, advanced markets for system services, comprehensive balancing schemes) were nevertheless of crucial importance.
- EU-wide instruments and the European rules on state aid have a significant impact on the policy mix and specific designs of policy instruments. The European Union Emissions Trading System (EU ETS, European Union (EU) 2014) is the only large-scale carbon pricing instrument for Germany and plays—in spite of the deep oversupply crisis of the system in its third and fourth phase (European Commission (EC) 2015b; European Environment Agency (EEA) 2015)—a key role in strategic decision making, not least of all because of its long-term cap trajectory. Limitations on state aid have been a topic of controversy between Germany and different EU institutions for many years, ranging from the phase-out of subsidies for hard coal mining to the design of remuneration mechanisms for renewable energies. Although the EU competences on energy are effectively inconsistent (EU-wide internal market for energy versus the free choice of energy mix by the member states), the European institutions have steadily succeeded in using their instruments of state aid control to establish a process of gradual convergence of specific policy designs.
- The German electricity system is highly interconnected with neighboring countries and regions; specific targets, efforts and policies of the EU (e.g., the ten year network development plans and the respective funding mechanisms) are explicitly geared to an increasing cross-border exchange of electricity, which

also increases the flexibility of the system to obtain increasing quantities of electricity generation from renewable energy sources.

Fourth, the public and political attitude is driven by significant risk aversions, especially with regard to security of supply and environmental or safety risks. Security of supply traditionally plays a major role in energy policy and had major implications for primary energy policies as well as the robustness of network infrastructures for more than half a century. As the only significant domestic traditional energy in Germany, coal has enjoyed strong political support since the 1950s when German hard coal mining lost its competitiveness against coal supplies from overseas. Heavy subsidies of hard coal mining secured domestic production over many years and only tighter restrictions in the framework of the European Union policies on state aid in the energy industry led to a phase-out of public subsidies by 2018, which will mark the end of domestic hard coal production in Germany. The situation is slightly different for domestic lignite mining, which to some extent depends on specific support policies (e.g., privileges taxation, planning, etc.) but not, however, at an order of magnitude that the German electorate was used to accepting in the case of hard coal over the course of many decades. Large-scale public support schemes for certain energy industries have thus been a familiar element of German energy policy. Another important aspect with regard to continuity of supply is the strong preference for extremely robust electricity and gas networks that allow for extremely low outage incidents, which amounts to 15 min annually for Germany, compared to approximately 60–80 min in the United Kingdom or 50–95 min in France (Council of European Energy Regulators (CEER) 2015). At the same time, it creates significant costs for the networks which amount to approximately 6.5 cents per kilowatt hour (ct/kWh) for low-voltage consumers, compared to 30% lower network costs for France or the United Kingdom. Although subject to debate from time to time, large-scale subsidies in the energy sector and a significant price for security/continuity of supply have nevertheless been persistent elements in German energy policy for a long time.

Since the early 1980s at least, environmental or safety concerns have played an equal or even more important role in public risk perception in German energy policy discourse. Based on longer traditions and starting with local or regional problems of acidification and forest damage in the 1970s, the public awareness of larger risks like nuclear or global climate change grew quickly during the 1980s. It led relatively quickly to changes in the political arena (the Green Party entered the Federal Parliament in 1983), regulatory action (federal legislation led to an enormous reduction of emissions from conventional pollutants in less than a decade) and institutional responses (foundation of a Federal Ministry for Nature Protection, the Environment and Reactor Safety in 1986 after the Chernobyl nuclear disaster) (Matthes 2000). From the late 1980s onwards, the public, political and scientific debate on environmental and safety risks has been dominated by risks with high levels of damage, according to the classification of German Advisory Council on Global Change (GACGC) (2000):

- the ‘Damocles’ type of large-scale nuclear risks, characterized by high extents of damage, based on Preiss et al. (2013) up to the sixfold of German GDP, but low probabilities of occurrence;
- the ‘Cassandra’ type of human-induced climate change, characterized by high extents of damage and high probabilities of occurrence.

German climate policy evolved as a policy built on a broad political consensus in the 1990s, whereas nuclear policy remained a highly controversial topic between the center-left (anti-nuclear) and center-right (mainly pro-nuclear) party coalitions, both of which were more or less equally strong.[1] After two nuclear policy swings towards a legally binding phase-out for nuclear power by approximately 2025 in 2000 and a lifetime extension for nuclear power plants of additional 8–14 years in 2010, the Federal Parliament voted in June 2011 in the aftermath of the nuclear disaster in Fukushima with an (untypical) overwhelming majority for a legally binding, stepwise phase-out of power generation from nuclear power plants by the end of 2022. The different decisions on nuclear energy were, however, embedded in a comprehensive energy policy program that targets a deep decarbonisation pathway with greenhouse gas emission reductions of 80 to 95% by 2050 (Bundesministerium für Wirtschaft und Energie (BMWi) 2015b). Table 1 indicates the comprehensive target framework which has formed the basis for Germany’s energy policy since 2010/2011. The explicit phase-out of nuclear energy by 2022 and the implicit phase-out of fossil fuels in the longer term (via the greenhouse gas emission reduction targets) require major progress in energy efficiency and the massive roll-out of renewable energies, with a strong focus on the electricity sector.

For the German electricity sector and its traditionally strong structural inertia, this strategic and regulatory framework requires new attempts of accelerated structural change which go beyond, and needs to be assessed and managed well beyond, the technological dimension of the emerging transition.

3 The driver: induced structural transformation of the energy system

German energy and electricity policy is effectively based on a specification of sustainability that is built on three pillars:

- Fossil fuels are non-sustainable in terms of resource-availability (in the very long term), and more importantly, non-sustainable because of their greenhouse gas emissions. Avoiding dangerous climate change (a ‘Cassandra’-type risk) requires for highly industrialized countries with a long record of carbon

[1] Some voting results in the German Federal Parliament might underline this balance: In the voting on the first formal nuclear phase-out legislation on 14th December 2001 the anti-nuclear motion received 345 votes and the pro-nuclear 324. In the voting for expanding the nuclear lifetime on 28th October 2010 the anti-nuclear motion received 280 votes and the pro-nuclear 309 (with two abstentions). In the voting on the return to an accelerated phase-out legislation after the Fukushima disaster the anti-nuclear motion received 513 votes on 30th June 2011, the pro-nuclear motion and abstentions accounted for only 79 and 8 votes respectively.

Table 1 German climate and energy target framework Source: German Federal Ministry for Economic Affairs and Energy (Bundesministerium für Wirtschaft und Energie (BMWi) 2015b)

	Targets: energy concept 2010 and …							… 2011
	GHG emissions (%)	Renewable energies		Energy efficiency				Nuclear power (%)
		Gross final consumption (%)	Power generation (%)	Primary energy (%)	Space heating (%)	Final energy (%)	Power consumption (%)	
2011								−41
2015								−47
2017								−54
2019								−60
2020	−40	18	35	−20	−20	−10	−10	
2021								−80
2022								−100
2030	−55	30	50					
2040	−70	45	65					
2050	−80 to −95	60	80	−50	−80	−40	−25	
Base year	1990	–	–	2008	2008	2005	2008	2010

emissions fast and deep decarbonisation of the economy, and especially of the power sector.

- Nuclear fuels are non-sustainable in terms of resource-availability and waste disposal (in the very long term), and more importantly, because of the lack of robustness resulting from the specifics of a 'Damocles'-type of risk which is characterized by extreme extents of potential damage—even if the probability of occurrence is relatively low.
- Renewable energy sources are sustainable within certain corridors. However, key restrictions need to be considered with regard to the sustainability of biomass use ('Cassandra'-type risks) and large hydropower dams ('Damocles'-type risks).

Preparing and complementing the public policy processes, a broad range of analytical evidence that underlines some key issues of the system transformation has been put forward in recent decades[2]:

- Available and foreseeable technologies and comprehensive assessments of the innovation pipelines indicate that the (emission abatement) potentials for achieving deep decarbonisation targets while concurrently phasing out nuclear power are available.
- To achieve the medium- and long-term decarbonisation targets, the necessary lead times, modernisation cycles and the structure and lifetime of capital stocks necessitate a specific focus on the sectors with long-lived capital stocks, strong infrastructure needs and medium-term innovation.
- The macroeconomic costs of an energy transition (for the whole energy system, including all energy sectors beyond the electricity system) also depend to some extent on the (counterfactual) costs of fossil fuels and conventional energy technologies but remain with less than 2% of GDP in 2050 at levels that are affordable for the economy in general. Economic challenges of specific importance will be the distributional effects, the transition costs, the structural changes in costs and revenues within the electricity sector as well as new economic appraisals.
- The number of interfaces between the new energy (electricity) system and society will increase if a new system evolves that includes a much more significant decentral segment and is much more infrastructure-intensive. Public acceptance with regards to new issues and in terms of new dimensions is also evolving as a critical element for the new energy system.

Figure 1 underlines the crucial unique dimension of timing for the energy transition decided upon in 2011. The German electricity system has seen different phases of growth and decline for different sources of electricity generation. However, never has a new source been introduced as quickly as in the case of renewables and never has the decline, and finally the phase-out been so steep as has

[2] See Matthes (2015) for a comprehensive list of the analytical work on energy transition and its implementation in Germany.

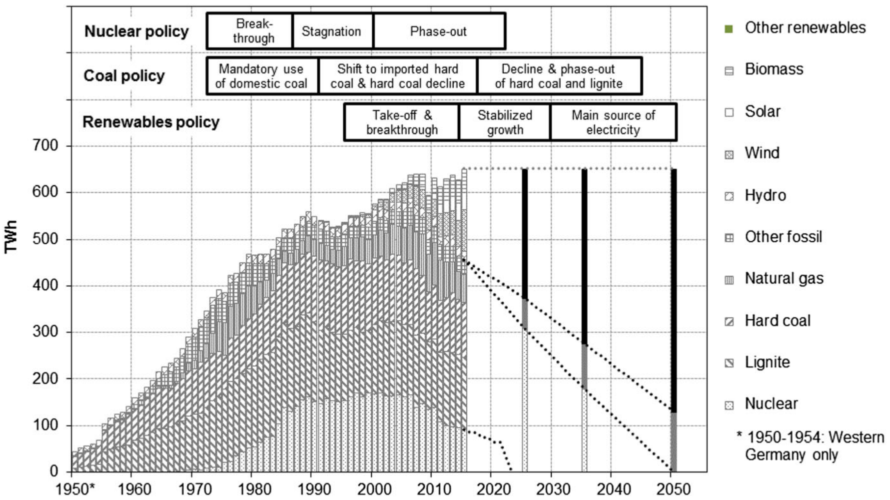

Fig. 1 Electricity generation in Germany and the phases of nuclear, coal and renewables policy, 1950–2050. Sources: Matthes (2000), updated by the author

been decided for nuclear power and at least planned for hard coal- and lignite-based power generation in the framework of the deep decarbonisation pathway up to 2050.

4 Structural changes in the electricity system

The massive roll-out of power generation from renewable energy sources evolved as the central element of German electricity policy over a period of two decades. These decades can be structured according to two main dimensions. First, the level of power generation from renewables and its impacts on the whole power system, and second, the evolution of the remuneration mechanism for power generation from renewables (Fig. 2).[3]

- The first phase (1990–2000) of this policy is characterized by experimenting with a new regulatory framework for renewable energies in the power sector but with only moderate increases of production levels. When the Electricity Feed-in Act (EFA) was introduced in 1990, thereby implementing a feed-in tariff for renewables, hydro power represented 92% of electricity from renewables with approximately 20 terawatt hours (TWh), the share of new renewables like wind, solar or modern biomass was negligible and the main renewable energy sources, i.e., hydropower and a much smaller part from organic waste incineration, delivered in total only 3.4% of total power generation (550 TWh). Over the course of ten years the feed-in tariffs triggered a significant increase of wind power generation, which reached, however, levels of less than 50% of the slightly increasing hydro power generation. In total, the share of renewables

[3] See BMWi (2015a and 2016) for further details on the historical trends and Öko-Institut and Fraunhofer ISI (2015) for further details on projections.

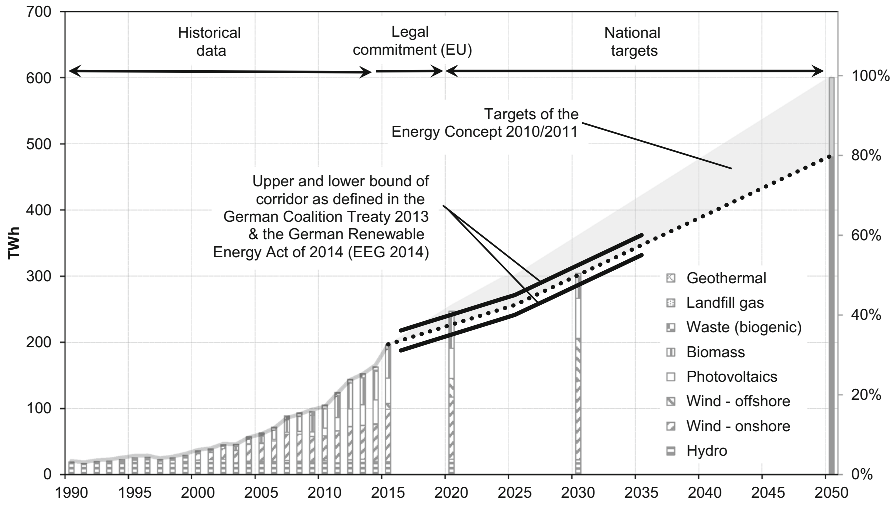

Fig. 2 Historical and planned development of power generation from renewable energy sources, 1990–2050. Source: Author's own calculations based on historical data from German Federal Ministry for Economic Affairs and Energy (BMWi 2016)

amounted to 6.3% of a moderately increasing total power generation (577 TWh).

- The experiences with the EFA led to a major overhaul of the scheme by the Renewable Energy Sources Act (RESA) in 2000, which marks the beginning of the second phase (2000–2010). It introduced a rather high level of technology differentiation from which solar power and modern biomass profited most and which were significantly more expensive than onshore wind power at the time. The continued boost for onshore wind led to production levels that almost quadrupled between 2000 and 2010 and an even more dynamic growth of solar photovoltaics (PV) and modern biomass. PV reached half of the almost constant hydro power levels and biomass exceeded it by almost 50% in 2010. In total, renewables represented 17% of a significantly increased total power generation in 2010 (633 TWh). This enormous increase of renewables, approximately 1 percentage point annually, and the significant decrease of the costs of wind and solar power was one of the experiences that supported the decisions in 2008, 2010 and 2011 to agree to ambitious legal commitments for the roll-out of renewables until 2020 in the framework of the European Union's Renewable Energy Directive (European Union (EU) 2009a) and to plan for an electricity system that draws at least 80% of total generation from renewables in 2050 (Bundesministerium für Wirtschaft und Technologie (BMWi), Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (BMU) 2010; Bundesministerium für Wirtschaft und Energie (BMWi) 2015b). A clear downside of this phase is that the instrument of legislatively fixed feed-in tariffs and the respective inertia did not keep pace with the dramatically decreasing costs of solar PV, which led to heavy overpayments for installations that were commissioned from 2009 to 2011 and the respective long-term cost burden within the remuneration mechanism for renewables.

- Although the introduction of this long-term perspective in 2010 marks a new, third phase (2010–2015), renewables still represented a niche segment of the power sector with a share of 17%. This had changed significantly by 2015 when renewables reached a share of 33%, driven by another doubling of onshore wind power, a quadrupling of solar PV and an increase of power generation from biomass by 50%. The new quality of impacts on the power system, the increasing costs of the traditional feed-in tariffs, significant decreases of costs for onshore wind power and solar PV as well as the absence of cost decreases for biomass led to major revisions of the RESA in 2014 and 2016. The remuneration scheme was transformed to Contracts for Difference (CfD) in 2014, the financing for biomass was drastically reduced and a 'target corridor' for the expansion of power generation from renewables was introduced as an element of quantity control that links the degression for the feed-in tariffs to the level of new investments.
- The ongoing fourth phase (2015 to approx. 2025) began first with the introduction of tenders as the main price formation mechanism which was essentially driven by the state aid rules within the European Union (European Commission (EC) 2014). Second, renewables began to change the price structures in the German and Central Western European power markets drastically. Generation options with short-term marginal costs of zero will deliver the full load for the first hours in the period from 2017 to 2020, reducing the residual load (the difference between load and production of power generation from variable renewables) and increasing the number of hours with wholesale market prices of zero or even at negative levels significantly. Third, the fourth phase also includes an attempt to buy down the costs of offshore wind generation to levels that are comparable to the levels achieved by onshore wind (6 to 10 ct/kWh, DWG 2015) and solar PV (7 to 12.5 ct/kWh, Bundesnetzagentur (BNetzA) 2016a, b). Irrespective of other changes in the remuneration scheme the success or failure of offshore wind will be an essential element of the fourth phase of renewable electricity roll-out. The results from the 2016 tender for offshore wind farms in the Netherlands (7.3 ct/kWh), however, indicate that significant progress can also be achieved on the learning curve for offshore wind energy, at least up to 2025.
- An indicative fifth phase (approx. 2025–2035), in which potential changes in the regulatory framework are no longer taken into account, will be characterized by the growing need for electricity storage because the number of hours without residual load will become significant (even if some flexibility of load is considered). Figure 3 presents the results of some illustrative modelling for future generation structures, which indicate that between 2025 and 2035 at least short-term storage options will emerge as essential elements of the system. Last but not least, the traditional structures of the electricity system with base medium and peak-load generation will gradually disappear.
- For shares of more than 75% renewables in total power generation the role of long-term electricity storage (large hydro reservoirs in Scandinavia or the Alp

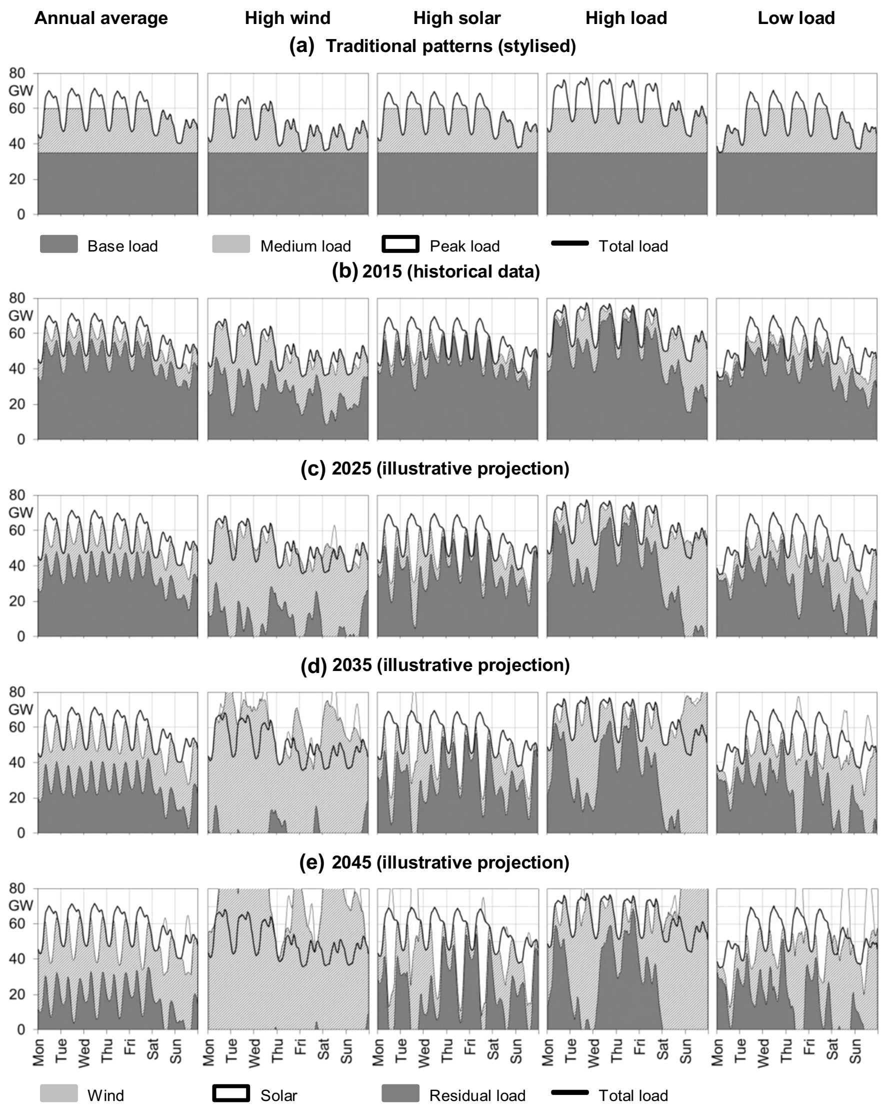

Fig. 3 Hourly wind, solar PV and residual generation for selected weeks, 2015–2045. Sources: Author's own calculations, based on data from the European Network of Transmission System Operators for Electricity (Entso-E) and the European Energy Exchange (EEX)

mountains, chemical storage, etc.) will evolve as one of the specific characteristics of the indicative sixth phase (2040 and beyond).

The transition of a traditional electricity system, dominated by fossil fuels and nuclear energy, to a system that is dominated by (variable) renewable energy sources has fundamental structural implications. First, the traditional structures of base, medium and peak-load generation (‘horizontal structure’) will be substituted by structures that depend on the much more variable yield renewable sources like solar and wind and the respective load situation (‘vertical structure’) that is much more diverse and strongly depends on effective coordination. Second, the system starts to depend significantly on elements that go beyond electricity generation (much more advanced system coordination, demand flexibility, the full range of storage options etc.) at least for the fifth and subsequent phases of the transition process. The respective costs and benefits as well the specific financing and coordination mechanisms need to be reflected in the design and the assessment of the transition process. Third, the availability of generation options that are suitable for decentralized implementation, even if the decentral segment coexists with more centralized segments, can change the system fundamentally. It opens the system to new players (from individuals to investors from other branches who have competitive advantages on the coordination of diverse systems), can bring in new economic perspectives and appraisals (e.g., self-consumption and other business models that are based on grid party and the respective indirect transfers) as well as financing options.

5 Economic implications: structural changes in the economics of the electricity system

The existing modelling evidence for the target structure of the energy transition suggests that the total system costs of different pathways towards largely decarbonized electricity systems do not differ significantly. Long-term comparisons with non-decarbonized, fossil- and nuclear-fuel based systems that consider the heavy re-investment needs of such systems suggest that the total system costs of renewable electricity systems, including flexibility options, storage, grid infrastructure, will culminate in approximately the same or even lower levels if fossil fuel prices recover to levels of around 100 US dollars per barrel (USD/bbl) and/or carbon prices of 50 Euro per metric ton of carbon dioxide (EUR/t CO_2) take effect (European Commission (EC) 2011b; Matthes 2012; Matthes et al. 2016). Even if the uncertainties regarding future progress on cost reductions remain significant, especially for solar PV, offshore wind energy but also with respect to integration costs of more system-suitable renewable generation options (weakwind turbines, East/West-installed PV installations, etc.); the system costs will be less vulnerable to volatile fuel markets.

Irrespective of the comparable levels of system costs a largely renewables-based electricity system will have significant structural differences to the traditional electricity systems:

- The system will be dominated by capital costs of generation and flexibility options as well as the additional grid infrastructures.

- With increasing shares of grid costs in the total system costs, a larger share of system costs will be subject to the price and investment regulation of natural (grid) monopolies.
- The price formation in the traditional wholesale markets will be dominated by zero short-term marginal cost options, which will decrease the revenue potential of these markets significantly and necessitate other market designs that are more suitable to enable investments and paybacks in generation, flexibility and storage options.
- The presumably larger share of decentralized generation options, essentially driven by the foreseeable costs reductions for solar PV and batteries, will create a market segment of self-generation, made viable by grid parity of the respective systems. If such market segments emerge beyond the niche, the traditional systems of infrastructure pricing and electricity taxation will be put at stake and subject to fundamental structural reforms (e.g., substitution of throughput-pricing by capacity-pricing).

Some of these issues have already materialized in the course of energy transition policies in Germany. On one hand, wholesale market prices in Germany are significantly lower than in neighboring countries, which are strongly interconnected to the German system and face the same fuel and CO_2 prices as Germany.

The comparison shown in Fig. 4 indicates the significant spot price differences in the wholesale markets of systems with strong interconnections and a largely integrated price formation as well as to systems with weak interconnections and price formation with different marginal generation units (gas in Spain, Italy and the UK, hydro in Scandinavia). The respective econometric analysis (Cludius et al. 2014) proves that a significant part of the price differences to the interconnected

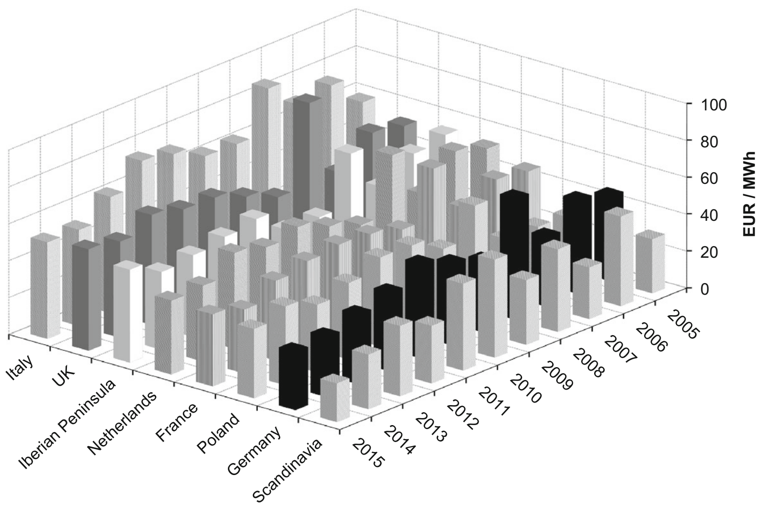

Fig. 4 Development of spot market prices on different European electricity exchanges, 2005–2015. Sources: EEX, EPEX, APX, UKPX, Nord Pool, GME, OMEL, TGE, ECB, author's calculations

systems may be attributed to the significant share of zero marginal cost renewables in the German markets. Even if the levelized cost of energy (LCOE) of renewables decrease further, increasing shares of renewables will not allow for sufficient payback of the necessary investments if income can only be generated from the traditional the energy-only markets. For medium shares of renewables (50% or less) this situation would be less challenging if fuel and CO_2 prices were significantly higher than at present but for higher shares of renewables even very high fuel and CO_2 prices would not allow for sufficient payback if the number of hours with zero or even negative prices in the wholesale markets would necessarily rise significantly.

As a consequence, remuneration mechanisms for (all) investments will emerge as a permanent element of a future power market design. The existing support schemes or renewables can thus be perceived as precursors of the respective elements of an economically sustainable future power market design. However, the experiences made with the existing remuneration scheme for renewables in Germany allow some lessons to be drawn for the future market design:

- The remuneration schemes for renewables of early movers cover significant innovation costs which will not occur again in future phases. The surcharge for renewables which covers the costs of the tariff for renewable power generators under the German RESA includes a share of 40% that covers the costs for creating a sufficiently sized and timed market for solar PV that made major cost reductions for this technology possible. In the phase from 2004 to 2012, which was crucial for the learning curve of solar PV, the demand from Germany was—with market shares of 25% to nearly 70%—a crucial driver for the cost reductions achieved on a global scale (Matthes et al. 2015).
- Elaborating a separate remuneration mechanism creates additional opportunities for policy-driven distributional targets. In the context of German industrial policy targets, significant parts of the industry (representing approximately one third of the total electricity consumption) are more or less completely exempted from any contribution to the remuneration scheme for renewables (Matthes et al. 2015). These exemptions, which represent approximately one third of the total costs of the scheme (€21bn in 2015), are to be compensated by higher contributions from non-privileged electricity consumers (private households, small and medium businesses, etc.) who pay a 50% higher surcharge than in the counterfactual situation without any exemptions for large parts of the industry. As a result, the roll-out of renewables in the German electricity system creates significant net benefits for those industries that can benefit from the price-decreasing effects of renewables in the wholesale markets (‘merit order effect’) without contributing to the remuneration scheme for renewables. In a country with a strong focus on strengthening the (wealthy) domestic industry and where the electricity bill represent approximately 2.5% of private expenditures for consumption, this might be perceived as acceptable for some time but for other economic environments more balanced approaches will probably be needed.
- The relatively high grid costs for residential and commercial electricity consumers (triggered by strong preferences for high levels of quality of supply,

approximately 65 EUR/MWh in 2015, ranging from 58 to 73 EUR/MWh in the period from 2006 to 2015, Bundesnetzagentur (BNetzA) and Bundeskartellamt (BKartA) (2016), relatively high surcharges for financing renewables (including a significant innovation premium and significant shares from distributional mechanisms for the benefit of the industry, growing from 20.5 to 63.5 EUR/MWh from 2010 to 2016, Bundesministerium für Wirtschaft und Energie (BMWi) 2015a), a relatively high tax on electricity (20.5 EUR/MWh since 2004) and a concession fee (going to municipal budgets, 16.6 EUR/MWh) are key determinants for relatively high retail prices for residential and commercial consumers. If costs for solar PV amounts to 120 EUR/MWh or (significantly) less and the costs for electric batteries continue to fall at the recent trajectories, a consumer price level of approximately 240 EUR/MWh (2016, excluding value added tax) is increasingly attractive for investments in self-generation. If the share of such self-generation exceeds the level of niche applications, alternative ways need to be found to finance grids or to compensate for losses for the federal or municipal budgets. If these alternative pricing or taxation structures are not implemented early enough, significant problems for investors in grid parity-based business models could occur, leading to a loss of investors' trust or making these necessary investments finally politically infeasible and potentially weakening the economic basis of the whole system.

In addition to this, the German experiences show that with regard to the cost dimension of the energy transition, comprehensive reflections need to be made on a broad range of cost elements and distributional effects of the transition process:

- A highly controversial issue is the cost of devaluation of existing assets caused by the policy-driven phase-in of clean energy sources and the design of a robust basis for recovering capital and fixed operational costs of the necessary system elements beyond the renewables (firm capacity, demand response, storage). The key challenge here is to separate the broader challenges (which can be observed in all European countries irrespective of their energy transition ambitions) for recovering fixed costs in a liberalized electricity system facing a low fuel and CO_2 price environment from the additional economic pressure that arises with the massive phase-in of wind and solar energy and its consequences for price structures in the market. The respective and highly controversial debate on whether capacity or capability markets will be required or not and the potential design of such mechanisms for Germany (BMWi 2014; Energiewirtschaftliches Institut an der Universität zu Köln (EWI) 2012; Enervis Energy Advisors (Enervis), BET Büro für Energiewirtschaft und technische Planung (BET) (2013), Öko-Institut, LBD Unternehmensberatung (LBD) 2015, 2012) led to a decision in 2015 to stay with an energy-only market with a strategic capacity reserve, built on the core belief that price spikes and volatility in the market will be sufficient to cover the fixed costs of the system (BMWi 2015). Establishing a sound, consistent and robust economic basis for the non-renewable system elements without preserving the high-carbon assets in the system is still,

however, an unsolved mid- and long-term challenge for a market design that builds a sustainable economic basis for the new energy system.
- The significant vulnerability of the transition pathway of a much more decentralized and infrastructure-depending electricity system to public acceptance will require implementation approaches that go beyond least-cost solutions in a more narrow sense (using cables instead of overhead lines to accelerate grid expansions or to make it feasible, avoiding large-scale distributional effects using potentially more costly implementation approaches etc.).
- The emerging complex system of generation, flexibility and storage options and grid infrastructure requires carefully planned policies and continuous (regulatory) processes. Avoiding costs related to discontinuities is an important approach to ensure a cost-effective transition process from the perspective of total system costs.

The complexity of the economic aspects of energy transition is also reflected in the role that cost-benefit analyses played in the discourse on energy transition. The long-term and macroeconomic ex ante cost-benefit analysis of the energy transition shows comparatively low net macroeconomic costs or even macroeconomic benefits. The findings on deviations of the gross domestic product (GDP) from the trend projection up to 2050, ranging from +1 to −1% and depending essentially on the fuel prices in the global energy markets (Energiewirtschaftliches Institut an der Universität zu Köln (EWI) 2014), built significant trust in the fact that energy transition is an appropriate strategy for the country. Short-term or sector policy-specific cost-benefit analyses in a narrow sense face significant difficulties in appropriately assessing the spillover effects in terms of technology costs and competitiveness of the domestic industry, especially for Germany as a country that is pioneering the transition process on one hand and has a strong focus on maintaining its industrial structures on the other hand. Against this background, the narrower cost-benefit analysis approaches have never played a significant role in the political and analytical discourse on energy transition in Germany. For the economic discourse, distributional effects and the affordability of the transition for the economy and the consumers played and plays a much more prominent role; however, this is always linked to the narrative of a technology-optimistic and sustainability-driven modernization strategy for a high-tech country with a population that has a strong awareness of environmental concerns and the crucial role of modern infrastructures.

These different dimensions clearly indicate that an energy transition goes beyond a technical restructuring; the changing economic structures of the system as well as the costs related to the dynamic transition process in all its dimensions need to be reflected carefully during the design of the market and regulatory arrangements that need to undergo their own transition process. Furthermore, the more complex technical and economic structures of the emerging new electricity system necessitate more complex evaluation indicators. The political focus on isolated cost elements of the system (be it costs of remuneration schemes or simply LCOE comparisons of single generation options) will mislead political decisions. Effective and efficient policies will always require an assessment of the full system costs over a longer time horizon, including consistent comparisons between counterfactual pathways instead of comparisons to systems that were historically built at costs that cannot be replicated in the future.

6 System implications: energy transition beyond the phase-in of zero emission sources

Energy transition is a process that will last several decades for most jurisdictions. The phasing-in carbon-free and renewable power generation options is certainly at the core of the transition but will not be sufficient if ambitious climate policy is seen as a key driver for this process when there are possible system feedbacks that can at least partly thwart the emission reduction effects of clean energy options.

Figure 5 depicts the changing structure of power generation and the CO_2 emissions from the German electricity system. It shows clearly that the rapid roll-out of power generation from renewable energy sources is not accompanied with the same dynamics of CO_2 emission reductions. This phenomenon results only to a small extent from the intended decrease of generation from nuclear power plants and more significantly from the decrease of low-CO_2 power generation from natural gas and the steady increase of net electricity exports from the remaining hard coal- and lignite-based plants. The shift to more CO_2-intensive generation options is essentially a result of the high spreads between natural gas and coal prices on one hand, and extremely weak CO_2 prices in the European Union Emissions Trading System (EU ETS) due to the ongoing huge allowance surplus in the scheme (European Commission (EC) 2015b; European Environment Agency (EEA) 2015).

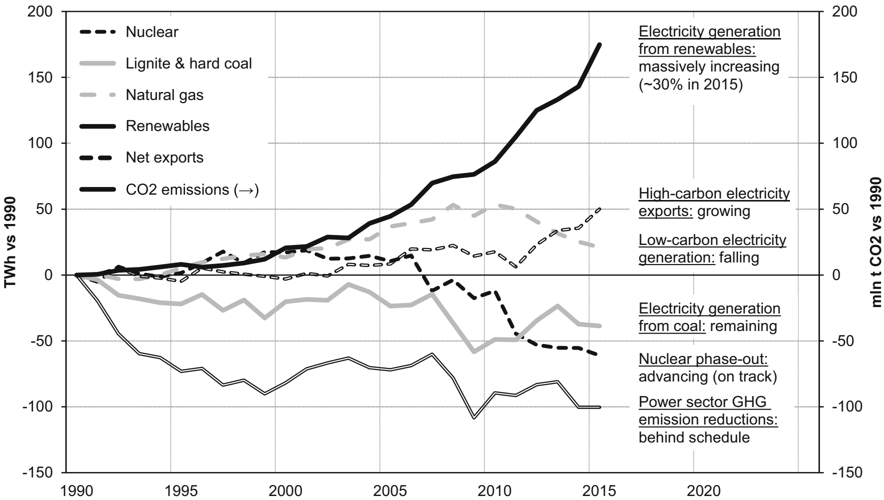

Fig. 5 Change of power generation by source, net electricity imports and power sector emissions in Germany, 1990–2015. Sources: Arbeitsgemeinschaft Energiebilanzen (AGEB), Umweltbundesamt (UBA), author's own calculations

The German example shows that an energy transition solely focused on the roll-out of low-risk and zero emission energy options is potentially not sufficient if the cumulative greenhouse gas emissions during the transition process are minimized as part of an effective climate policy. It requires policy and regulatory approaches that incentivize in parallel the fuel switch to low-CO_2 generation options as well as disinvestments from high carbon and to some extent outdated power plants. Carbon pricing policies may play a key role on all abatement options and there are few alternatives in terms of emission reductions by a cleaner dispatch. For effective disinvestment strategies, a broader range of policy tools is available; Germany took first steps in this respect in 2016 by offering decommissioning premiums of up to 2 billion Euros in total to outdated plants with high CO_2 emissions that represent 10% of the capacity of the incumbent lignite fleet (European Commission (EC) 2016).

The need for parallel tracks of phase-in of zero carbon options as well as decreasing the CO_2 intensity of the (at least temporarily) remaining fossil generation fleet requires careful considerations on the interactions between the different elements of real-world policy mixes (Matthes 2010; International Energy Agency (IEA) 2011, 2016). Especially, if carbon pricing policies are based on approaches of quantity control like emission trading systems (ETS) the interactions between ETS and remuneration schemes for zero emission generation options need to be reflected by careful and comprehensive ex ante planning for the complementary policy tools or specific mechanisms that allow for adjustments of the number of allowances which are available for the emitting entities (the planned Market Stability Reserve for the EU ETS is an element of such attempts, others are price corridors or options for automatic cancellation of allowances in accordance with the outcomes of complementary policies to an ETS).

7 Diversity implications: changes in the diversity and ownership structures of the electricity system

An energy transition towards renewable energy source will lead to a much more diversified electricity system. On one hand, this applies with regard to the quantitative dimension. Significantly smaller unit sizes of generation units will lead to huge increases in the numbers of power generators. The traditional German power system was based on approximately 500 large generation units, whereas the fast growing renewable segment of the system consisted of approximately 1.81 million generation units (of which 1.77 million PV installations with an installed capacity of 40 GW and 27,400 wind power plants with an installed capacity of 47 GW) in mid-2016.

This magnitude of generation units at a level of approximately one third of power generation indicates the new quality of coordination needs in the future electricity system. This is even more important and a more significant challenge if the shift in ownership structures is taken into the consideration. The German fleet of power plants was traditionally owned for approximately 80% by 9 large utilities (Matthes 2000); after a series of mergers among these corporations only 4 utilities (RWE, E.ON, Vattenfall Europe and EnBW) exist in the market. The remaining share of approximately 20% was distributed among municipal utilities and industrial self-generation. With the increasing shares of renewables in the electricity sector, qualitatively new ownership structures can be observed. The major four utilities represent only 5% of the installed capacity in renewables, and the other, mainly municipal utilities alone have a bigger share at 7%. The major share of the capacities is, however, owned by a significant diversity of newcomers in the electricity sector (Fig. 6).

Individuals represent the biggest single segment (35%) but also industry, farmers, project developers and funds or banks own significant shares of renewable power generation capacities. These changing patterns of ownership structure have important implications for the electricity system as well as electricity policy:

- The economic participation in the project of energy transition improves the acceptance and the interest in important constituencies (i.e., individuals and farmers) which increases the political robustness of the project.
- The capabilities to deal with complex electricity system management and regulation issues is limited and definitively less well advanced than in the traditional utilities. As a consequence, a balance needs to be found between reducing the complexity of the system rules and operations (to the extent feasible) and the capability of service providers that quickly entered the market and play an important role in the coordination of the system.

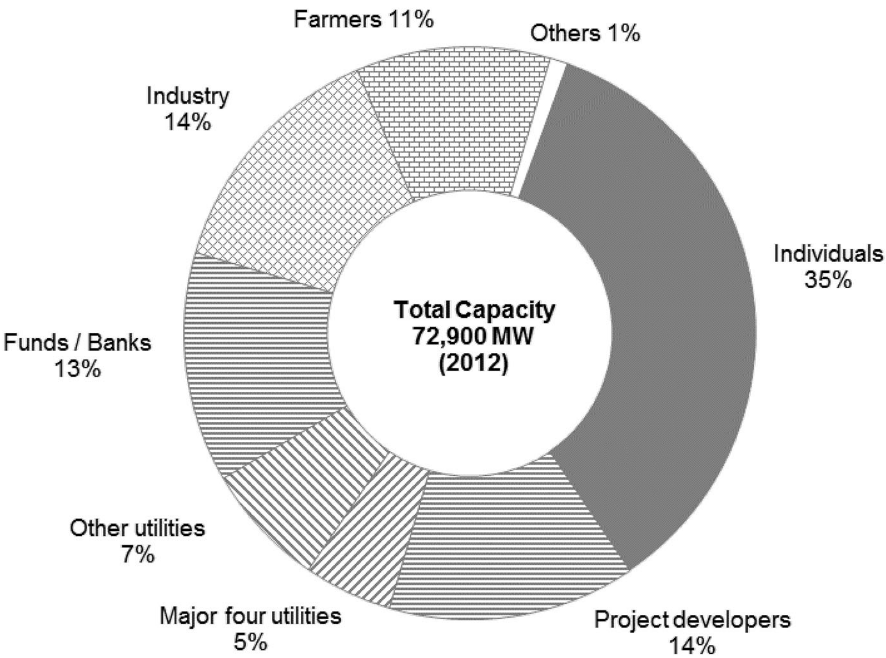

Fig. 6 Ownership structure of renewable power generation capacities, 2012 Source: trend:research and Leuphana Universität Lüneburg (2013); trend:research (2014)

- With the at least partly decreasing size of the projects and the more diverse structure of investors the access to financing sources has improved significantly. More players from the finance industry have become active (e.g., local banks), and equally importantly, the requirements for return on investment decreased, at least for the segments of investors with less attractive investments in low-yield government bonds, etc.
- At least (politically important) parts of the new investors (individuals, farmers) have different approaches of risk perception. Parallel to the lower requirements on returns on investment and the lower implementation risks because of stronger local ties significant aversions against advance investments (i.e., investments necessary before financing can be secured) can be observed.
- Economic and financial appraisals changed at least for the segment of individuals. Apart from the trend towards self-generation (which from a system perspective is also challenging), the attitude to investments has changed from the traditional 'investment good' approach to a 'consumption good' perspective.

In addition to these electricity sector-specific issues, the traditionally strong preferences for decentralized structures in German society, policies and politics in a broader context might also explain the key importance of this new diversity in the power sector in the German electricity policy discourse. As a result, general and overarching political strategies as well as the specification of the regulatory framework and the market design increasingly need to consider these new and—with increasing shares of renewables—increasingly important structures of investors, owners and operators and find balanced approaches:

- to develop market structures that allow a coordination of the scheme based on price signals because this is the only coordination mechanism that can handle such diverse structures for the development phases of the scheme beyond the niche (which already has 1.8 million players);
- to consider the important role of new market participants as individuals, farmers or project developers (in terms of public and political acceptance, financing, etc.) by maintaining a level of complexity and needs for expertise that can be handled by these players or respective service providers with reasonable efforts;
- to deal with the (existing and potentially increasing) risk asymmetries between the new and the old segment of the electricity system and market; and
- that comply with the existing and emerging rules and provisions of the internal EU electricity market as well as the state aid regime of the EU.

Maintaining an appropriate diversity of participants as a separate and specific goal of electricity policy has been subject to complex and heated debates in recent years but has, however, factually evolved as one of the important determinants of policy designs. The potential (but nevertheless limited) losses in cost efficiency have been effectively lower ranked than the increase in robustness of the energy transition pathway.

8 Infrastructure implications: changes in the spatial structures of electricity system

The ongoing and future transition of the German electricity system has strong implications on the spatial patterns of the electricity system. Again, these spatial patterns have been subject to fundamental changes in the past (e.g., when nuclear power was phased-in during the 1970s) but hardly at the level and with the speed that is required by the recent transition pathway. Figure 7 shows a schematic representation of the traditional and the new structures of electricity generation. The nuclear phase-out by 2022 and a slightly more gradual phase-out of coal-based generation will leave supply gaps in certain regions that contain strong industrial power consumption on the one hand. On the other hand, regions in the Northern part of the country with a strong supply of wind (and party solar energy) that are often less densely populated and have fewer restrictions on land use, have a strong and significantly increasing surplus of electricity supply.

As a result, large upgrades of the transmission grids are required, which still represent the incumbent structures of electricity supply and demand, including four major lines from the North to the South of Germany that will be implemented with DC (direct current) technology, which is a new element in the German electricity system apart from rather small cable connections to Scandinavia and the connection of offshore wind farms. A comprehensive but complicated process of electricity network planning has been established, which includes a level of public participation that has been unknown in German electricity policy.[4] After several rounds of planning and licensing that created major delays for the network upgrades (Bundesnetzagentur (BNetzA) 2016c) some crucial issues emerged:

- There has been strong resistance from individuals and communities who are affected by the new transmission line projects. Sensitive planning, adapting local alternatives and using alternative technologies (using cables instead of overhead lines for significant parts of the projects) and the respective reflections in the regulatory process (to allow significantly more costly options like DC cables) have proved to be key elements to enable these projects (Hertz Transmission (50 Hertz) 2016).
- There has been strong resistance from several parts of the policy arena, including Federal States like Bavaria, that the new transmission line projects will be less used for the transport of electricity from renewables to other parts of the country and more to secure the production of the still significant part of coal-based power generation in the East and the West of the country or to strengthen cross-border electricity trade (which is clearly a goal for the EU's support of some projects, European Commission (EC) 2015a). Embedding the infrastructure planning in a policy framework that takes a more accountable-oriented approach to handling the phase-out of coal-based generation is emerging as a key challenge for electricity policy, underlining again the need for comprehensive policy decisions that make the structural change more visible and accountable to the public.

[4] See http://www.netzentwicklungsplan.de/en for further details, documents, maps and data.

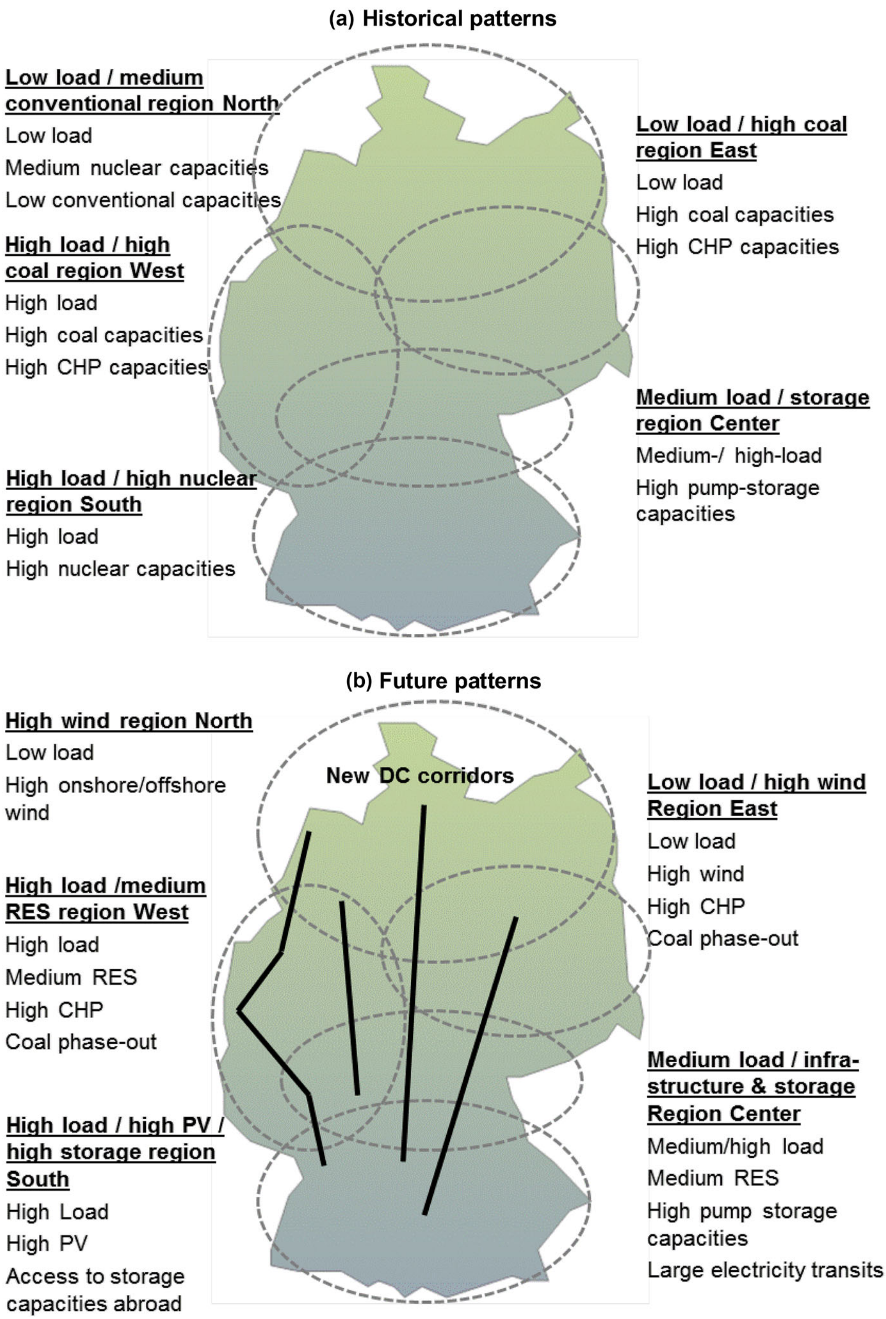

Fig. 7 The historical and the emerging spatial pattern of the German electricity system Source: Author's own representation

- An unsolved issue is the differentiation of regional burdens that are related to a massive infrastructure roll-out. The regions with strong power production from renewables have a strong interest in upgrading the infrastructure to maintain regional production and value added. The regions with strong import needs (and often a strong industrial basis) have an interest in additional infrastructure because they have an interest in relatively cheap power generation from wind and in high levels of security and quality of supply. The key problems in this respect are the regions which have no major surplus production or import needs but ensure the transit from North to South. Appropriate regional compensation mechanisms still need to be developed and tested.

The need for adjustments in the network infrastructure is, however, not limited to the transmission grids. Most of the renewable generators are connected to distribution networks that also require upgrades to manage stronger flows of electricity on the one hand and multidirectional flows on the other hand. The key challenge here is less public acceptance than adjustments in the incentive regulation scheme to build an enabling regulatory framework at the level of distribution networks.

Building an enabling network infrastructure with all its implications (cables, community-friendly location, etc.) certainly comes at a cost that mainly represents the opportunity costs of public acceptance in a democratic society. Compared to the counterfactual investment needs these costs (from a regulated business) amount to 10–20% higher network costs for the next phase of the energy transition. These costs need to be reflected in the system costs but nevertheless do not change the overall economic assessment of a decarbonized electricity system.

9 Conclusions

The energy transition has reached a level that goes beyond a niche for the power generation from renewables but which nevertheless faces qualitatively new phases of the transition process. Even if a series of structural elements of the new system are still uncertain and unknown, given the ongoing processes of innovation but also the changing policy arenas, some structural characteristics of the future electricity system in Germany seem to be robust:

- It shall be nuclear-free and low CO_2 emitting for the mid-term and carbon-free for the longer term;
- It will be significantly more energy efficient but not necessarily have lower consumption as a result of the increasing electrification of the energy system;
- It will be much more diverse with a view to technology options, the mix and interactions of centralized, distributed and decentralized elements, economic perspectives and appraisals, etc.;
- It will rely much more, but nevertheless not exclusively, on distributed and decentralized options;

- It will be much more coordination-intensive with regard to investments and operations;
- It will be much more capital-intensive with regard to renewable generation options, flexibility options, storage and network infrastructure;
- It will be more infrastructure-intensive and require comprehensive and complex planning and regulators efforts;
- It will be much more sensitive to public acceptance, especially with a view to decentralized generation options like onshore wind power and network infrastructures;
- It will not be significantly more expensive than the counterfactual pathway of the electricity systems over the course of the next decades (when the financing of upfront investments in key innovations like solar PV, offshore wind and battery technologies expired).

Based on these characteristics of the future electricity system, the transition process needs to be based on a comprehensive policy mix which is essentially based on essentially four pillars:

1. Paving the way for clean generation and the complementary flexibility and storage options: The respective policies needs to create an appropriate market design that enables both investments as well as efficient operations but also reflects the opportunity costs of broad public and political acceptance, and thus the robustness of the transition pathway.
2. Designing the exit game for the CO_2-intensive capital stocks: The transition process towards a decarbonized electricity system will, at least in Germany, be faster than the regular modernization cycles and be vulnerable to global fuel market trends (coal–gas price spreads, etc.). For a robust transition process, an active management for phasing-out high-carbon assets will be necessary, which goes beyond the carbon pricing approach of the EU ETS if this instrument cannot be reanimated at a sufficiently early point in time.
3. Triggering the network infrastructures in time: The emerging spatial and regional patterns of power generation and demand need to be reflected. The processes for planning and licensing need to ensure as much robustness in terms of public acceptance as possible. The regulatory framework needs to attract investments on a large scale and the long lead times of infrastructure roll-outs limited to the degree to which fully technology- and siting-neutral approaches can be implemented for the roll-out of renewable power generators.
4. Making innovation work in time: For the longer-term key innovations will be necessary for technologies (e.g., energy storage, network infrastructure), business models (e.g., demand response) and regulatory approaches (e.g., dealing with self-generation). Targeted innovation efforts as well as early piloting are crucial elements for Germany but also in the broader context of the EU to have innovative solutions available at the stage of the energy transition at which they will be needed.

Accepting energy transition as a broader structural change that goes beyond simple substitutions of technologies and introduces a respective system management that is based on clear principles and reflects effectiveness, economic efficiency, robustness and enhancing the capabilities of learning will be a fundamental basis for making energy transition a success beyond its present stage and the electricity system future-proof.

Acknowledgements The author would like to thank the organizers of the Fourth International Symposium on Human Survivability at Kyoto University who sparked the work on a comprehensive overview of the energy transition in Germany and the two anonymous reviewers for their valuable comments and suggestions which helped to improve the quality of the paper. The author gratefully acknowledges the helpful editorial assistance of Vanessa Cook on the draft.

Compliance with ethical standards

Conflict of interest No conflict of interest exists with regard to this article.

References

Bundesministerium für Wirtschaft und Energie (BMWi) (2015a) EEG in Zahlen: Vergütungen, Differenzkosten und EEG-Umlage 2000 bis 2016. Berlin, 15 October 2015. http://erneuerbare-energien.de/EE/Redaktion/DE/Downloads/eeg-in-zahlen-pdf.pdf?__blob=publicationFile. Accessed 25 August 2016

Bundesministerium für Wirtschaft und Energie (BMWi) (2015b) Die Energie der Zukunft. Vierter Monitoring-Bericht zur Energiewende. Berlin, November 2015. http://www.bmwi.de/BMWi/Redaktion/PDF/V/vierter-monitoring-bericht-energie-der-zukunft,property=pdf,bereich=bmwi2012,sprache=de,rwb=true.pdf. Accessed 25 August 2016

Bundesministerium für Wirtschaft und Energie (BMWi) (2016) Zeitreihen zur Entwicklung der erneuerbaren Energien in Deutschland. Berlin, February 2016. http://www.erneuerbare-energien.de/EE/Redaktion/DE/Downloads/zeitreihen-zur-entwicklung-der-erneuerbaren-energien-in-deutschland-1990-2015.pdf?__blob=publicationFile&v=6. Accessed 25 August 2016

Bundesministerium für Wirtschaft und Technologie (BMWi), Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (BMU) (2010) Energiekonzept für eine umweltschonende, zuverlässige und bezahlbare Energieversorgung. Berlin, 28.09.2010. https://www.bmwi.de/BMWi/Redaktion/PDF/E/energiekonzept-2010,property=pdf,bereich=bmwi2012,sprache=de,rwb=true.pdf. Accessed 25 August 2016

Bundesnetzagentur (BNetzA) (2016a) Hintergrundpapier Ergebnisse der vierten Ausschreibungsrunde für Photovoltaik (PV)-Freiflächenanlagen vom 1. April 2016. Bonn. http://www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Sachgebiete/Energie/Unternehmen_Institutionen/ErneuerbareEnergien/PV-Freiflaechenanlagen/Gebotstermin_01_04_2016/Hintergrundpapier_01_04_2016.pdf?__blob=publicationFile&v=5. Accessed 25 August 2016

Bundesnetzagentur (BNetzA) (2016b) Bestimmung der Förderssätze für Fotovoltaikanlagen § 31 EEG 2014 für die Kalendermonate Juli 2016, August 2016 und September 2016. Bonn. http://www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Sachgebiete/Energie/Unternehmen_Institutionen/ErneuerbareEnergien/Photovoltaik/Datenmeldungen/DegressionsVergSaetze_Juli-Sep2016.xls?__blob=publicationFile&v=3. Accessed 25 August 2016

Bundesnetzagentur (BNetzA) (2016c) EnLAG-Monitoring. Stand des Ausbaus nach dem Energieleitungsausbaugesetz (EnLAG) zum ersten Quartal 2016. Bonn. http://www.netzausbau.de/SharedDocs/Downloads/DE/Vorhaben/EnLAG/EnLAG-Bericht.pdf?__blob=publicationFile. Accessed 25 August 2016

Bundesnetzagentur (BNetzA), Bundeskartellamt (BKartA) (2016) Monitoring Report 2015. Bonn. http://www.bundesnetzagentur.de/SharedDocs/Downloads/EN/BNetzA/PressSection/ReportsPublications/2015/Monitoring_Report_2015_Korr.pdf?__blob=publicationFile&v=4. Accessed 25 August 2016

Cludius J, Herrmann H, Matthes FC, Graichen V (2014) The merit order effect of wind and photovoltaic electricity generation in Germany 2008–2016: Estimation and distributional implications. Energy Econ 44:302–323

Council of European Energy Regulators (CEER) (2015) CEER Benchmarking Report 5.2. on the Continuity of Electricity Supply. Data update. Ref: C14-EQS-62-03, Brussels, 12 February 2015. http://www.ceer.eu/portal/page/portal/EER_HOME/EER_PUBLICATIONS/CEER_PAPERS/Electricity/Tab4/C14-EQS-62-03_BMR-5-2_Continuity%20of%20Supply_20150127.pdf. Accessed 25 August 2016

Deutsche WindGuard (2015) Kostensituation der Windenergie an Land in Deutschland–Update. Varel, December 2015. https://www.wind-energie.de/sites/default/files/download/publication/kostensituation-der-windenergie-land-deutschland-update/20151214_kostensituation_der_windenergie_an_land_in_deutschland_update.pdf. Accessed 25 August 2016

Energiewirtschaftliches Institut an der Universität zu Köln (EWI) (2012) Untersuchungen zu einem zukunftsfähigen Strommarktdesign. Report commissioned by German Federal Ministry for Economic Affairs and Energy, Cologne, March 2012. http://www.bmwi.de/BMWi/Redaktion/PDF/Publikationen/endbericht-untersuchungen-zu-einem-zukunftsfaehigen-strommarktdesign.pdf. Accessed 25 August 2016

Energiewirtschaftliches Institut an der Universität zu Köln (EWI), Prognos and Gesellschaft für Wirtschaftliche Strukturforschung (GWS) (2014) Entwicklung der Energiemärkte—Energiereferenzprognose. Study commissioned by German Federal Ministry for Economic Affairs and Technology, Basle, Cologne, Osnabrück, June 2014. http://www.bmwi.de/BMWi/Redaktion/PDF/Publikationen/entwicklung-der-energiemaerkte-energiereferenzprognose-endbericht,property=pdf,bereich=bmwi2012,sprache=de,rwb=true.pdf. Accessed 25 August 2016

Enervis Energy Advisors (Enervis) and BET Büro für Energiewirtschaft und technische Planung (BET) (2013) Ein zukunftsfähiges Energiemarktdesign für Deutschland. Study commissioned by German Association of Local Utilities (VKU), Berlin, Aachen, March 2013. http://www.enervis.de/images/stories/enervis/pdf/publikationen/gutachten/emd_gutachten_langfassung_enervis_bet_vku_20130301.pdf. Accessed 25 August 2016

European Commission (EC) (2008) 20 20 by 2020. Europe’s climate change opportunity. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. COM(2008)30 final, Brussels, 23.01.2008. http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52008DC0030&from=EN. Accessed 25 August 2016

European Commission (EC) (2011a) A Roadmap for moving to a competitive low carbon economy in 2050. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. COM(2011)112 final, Brussels, 08.03.2011. http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52011DC0112&from=EN. Accessed 25 August 2016

European Commission (EC) (2011b) Energy Roadmap 2050. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. COM (2011) 885 final, Brussels, 15.12.2011. https://ec.europa.eu/energy/sites/ener/files/documents/2012_energy_roadmap_2050_en_0.pdf. Accessed 25 August 2016

European Commission (EC) (2014) Guidelines on State aid for environmental protection and energy 2014-2020. Communication from the Commission (2014/C200/01), Official Journal of the European Union C200/1-55, 28.06.2014. http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52014XC0628%2801%29&from=EN. Accessed 25 August 2016

European Commission (EC) (2015a) Commission delegated Regulation (EU) 2016/89 of 18 November 2015 amending Regulation (EU) No 347/2013 of the European Parliament and of the Council as regards the Union list of projects of common interest. Official Journal of the European Union L19/1-21, 27.01.2016. http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32016R0089&from=EN. Accessed 25 August 2016

European Commission (EC) (2015b) Carbon Market Report 2015. COM(2015)576 final, Brussels, 18.11.2015 http://ec.europa.eu/clima/policies/strategies/progress/docs/com_2015_576_annex_1_en.pdf. Accessed 25 August 2016

European Commission (EC) (2016) State Aid SA. 42536 – Germany. Closure of German lignite-fired power plants. C(2016) 3124, Brussels, 27.5.2016. http://ec.europa.eu/competition/state_aid/cases/261321/261321_1762503_157_2.pdf. Accessed 25 August 2016

European Environment Agency (EEA) (2015) Trends and projections in the EU ETS in 2015. EEA Technical report No. 14/2015, Luxembourg: Publications Office of the European Union, 2015. http://www.eea.europa.eu/publications/trends-and-projections-eu-ets-2015/at_download/file. Accessed 25 August 2016

European Union (EU) (1996) Directive 1996/92/EC of the European Parliament and of the Council of 19 December 1996 concerning common rules for the internal market in electricity. Official Journal of the European Union L27/20-29, 30.01.1997. http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:31996L0092&from=EN. Accessed 25 August 2016

European Union (EU) (2003) Directive 2003/54/EC of the European Parliament and of the Council of 26 June 2003 concerning common rules for the internal market in electricity and repealing Directive 96/92/EC. Official Journal of the European Union L176/37-55, 15.07.2003. http://eur-lex.europa.eu/resource.html?uri=cellar:caeb5f68-61fd-4ea8-b3b5-00e692b1013c.0004.02/DOC_1&format=PDF. Accessed 25 August 2016

European Union (EU) (2009a) Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. Official Journal of the European Union L140/16-62, 05.06.2009. http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32009L0028&from=EN. Accessed 25 August 2016

European Union (EU) (2009b) Directive 2009/72/EC of the European Parliament and of the Council of 13 July 2009 concerning common rules for the internal market in electricity and repealing Directive 2003/54/EC. Official Journal of the European Union L211/55-93, 14.08.2009. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:211:0055:0093:EN:PDF. Accessed 25 August 2016

European Union (EU) (2014) Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC. Official Journal of the European Union 2003L87/1-67, 30.04.2014. http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02003L0087-20140430&from=EN. Accessed 25 August 2016

Federal Ministry for Economic Affairs and Energy (Bundesministerium für Wirtschaft und Energie, BMWi) (2014) An Electricity Market for Germany's Energy Transition, Discussion Paper of the Federal Ministry for Economic Affairs and Energy (Green Paper). Berlin, October 2014. https://www.bmwi.de/BMWi/Redaktion/PDF/G/gruenbuch-gesamt-englisch,property=pdf,bereich=bmwi2012,sprache=de,rwb=true.pdf. Accessed 25 August 2016

Federal Ministry for Economic Affairs and Energy (Bundesministerium für Wirtschaft und Energie, BMWi) (2015) An electricity market for Germany's energy transition, White Paper by the Federal Ministry for Economic Affairs and Energy. Berlin, July 2015. http://www.bmwi.de/English/Redaktion/Pdf/weissbuch-englisch,property=pdf,bereich=bmwi2012,sprache=en,rwb=true.pdf. Accessed 25 August 2016

German Advisory Council on Global Change (GACGC) (2000) World in Transition. Strategies for Managing Global Environmental Risks. Springer: Berlin, Heidelberg, New York, Barcelona, Hong Kong, London, Milan, Paris, Singapore, Tokyo. http://www.wbgu.de/fileadmin/templates/dateien/veroeffentlichungen/hauptgutachten/jg1998/wbgu_jg1998_engl.pdf. Accessed 25 August 2016

Hertz Transmission (50 Hertz), Amprion, Tenne T TSO and Transnet BW (2016) Netzentwicklungsplan Strom. Version 2015, Zweiter Entwurf der Übertragungsnetzbetreiber, Berlin, 29 February 2016. http://www.netzentwicklungsplan.de/_NEP_file_transfer/NEP_2025_2_Entwurf_Teil1.pdf. Accessed 25 August 2016

International Energy Agency (IEA) (2011) Summing up the parts. Combining Policy Instruments for Least-Cost Climate Mitigation Strategies. IEA Information Paper, Paris, September 2011. https://www.iea.org/publications/freepublications/publication/Summing_Up.pdf. Accessed 25 August 2016

International Energy Agency (IEA) (2016) Re-powering markets. Market design and regulation during the transition to low-carbon power systems. Paris. https://www.iea.org/publications/freepublications/publication/REPOWERINGMARKETS.pdf. Accessed 25 August 2016

Matthes FC (2000) Stromwirtschaft und deutsche Einheit: eine Fallstudie zur Transformation der Elektrizitätswirtschaft in Ost-Deutschland. Berlin

Matthes FC (2010) Greenhouse gas emissions trading and complementary policies. Developing a smart mix for ambitious climate policies. Report commissioned by German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. Öko-Institut: Berlin, June 2010. http://www.oeko.de/oekodoc/1068/2010-114-en.pdf. Accessed 25 August 2016

Matthes FC (2012) Langfristperspektiven der europäischen Energiepolitik–Die Energy Roadmap 2050 der Europäischen Union. Energiewirtschaftliche Tagesfragen 62 (2012) H. 1/2, 50-53. http://www.et-energie-online.de/Portals/0/PDF/zukunftsfragen_2012_01_matthes.pdf

Matthes FC (2015) Case Study 1: The Energy Transition in Germany. In: Centre on Regulation in Europe (CEER): Towards a low carbon European power sector. The energy transition in Europe: initial lessons from Germany, the UK and France. Brussels, 6 October 2015, 48–86. http://www.cerre.eu/sites/cerre/files/151006_CERREStudy_EnergyTransition_Final.pdf. Accessed 25 August 2016

Matthes F, Haller M, Loreck C, Cook V (2015) Die Umlage des Erneuerbaren-Energien-Gesetzes (EEG). Hintergründe, Trends, Treiber und Perspektiven. Report commissioned by Baden-Württemberg Ministry for Environment, Climate and Energy, Öko-Institut: Berlin, 8 November 2015. http://www.oeko.de/oekodoc/2448/2015-605-de.pdf. Accessed 25 August 2016

Matthes F, Heinemann C, Ludig S, Cook V (2016) Die Gesamtkosten regenerativer Stromsysteme im Vergleich. Berlin (forthcoming)

Öko-Institut and LBD Unternehmensberatung (LBD) (2015) Die Leistungsfähigkeit des Energy-only-Marktes und die aktuellen Kapazitätsmarkt-Vorschläge in der Diskussion. Study commissioned by Baden-Württemberg Ministry for Environment, Climate and Energy and the Bavarian State Ministry for Economy, Media, Energy and Technology. Berlin, February 2015. http://www.oeko.de/oekodoc/2218/2015-003-de.pdf. Accessed 25 August 2016

Öko-Institut, LBD Unternehmensberatung (LBD), and Raue LLP (2012) Focused capacity markets. A new market design for the transition to a new energy system. Study commissioned by WWF Germany. Berlin, 8 October 2012. http://www.oeko.de/oekodoc/1631/2012-004-en.pdf. Accessed 25 August 2016

Preiss P, Wissel S, Fahl U, Friedrich R, Voß A (2013) Die Risiken der Kernenergie in Deutschland im Vergleich mit Risiken anderer Stromerzeugungstechnologien. Universität Stuttgart, Institut für Energiewirtschaft und Rationelle Energieanwendung, Working Paper No. 13, Stuttgart, February 2013. http://www.ier.uni-stuttgart.de/publikationen/arbeitsberichte/downloads/Arbeitsbericht_11.pdf. Accessed 25 August 2016

trend:research (2014) Anteile einzelner Marktakteure an Erneuerbare Energien-Anlagen in Deutschland (3. Auflage). Trend:research: Bremen

trend:research and Leuphana Universität Lüneburg (2013): Definition und Marktanalyse von Bürgerenergie in Deutschland. Bremen, Lüneburg, October 2013. https://www.buendnis-buergerenergie.de/fileadmin/user_upload/downloads/Studien/Studie_Definition_und_Marktanalyse_von_Buergerenergie_in_Deutschland_BBEn.pdf. Accessed 25 August 2016