Systemic Consequences 8

The aim of this chapter is to bring out the inevitable consequences for the concrete energy landscape in Germany that will emerge due to the *Energiewende* as we have described it in terms of targets, motives and framework conditions. We refer to these as the *systemic consequences* of the *Energiewende*.

8.1 Types of Renewable Energy 1

If one of the three targets of the *Energiewende* is defined as "expansion of renewable energies to at least 80% of Germany's electricity generation", this does not yet constitute a statement about which of the currently available technologies in the field of renewable energy should be used here. So we will first address the question: Which renewable technologies should be expediently used in the *Energiewende*?

As of today, in Germany the following technologies can be considered viable in terms of technological maturity, permitting the performance of an RE plant to be largely predictable (in terms of power output, electricity production, service life, effects on the immediate environment, costs, etc.):

– Hydropower plants (running water)
– Biomass plants (biogas, wood, domestic waste)
– Wind turbines on land (onshore)
– Wind turbines at sea (offshore)
– PV systems

It is quite possible that there will be technological advances made during the next few decades that will allow the use of other types of renewable energy and so will play a role in the future implementation of the *Energiewende* (e.g. geothermal power plants, tidal power stations and others). However, it is obvious that the question posed at the beginning of this section must be answered regardless.

T. Unnerstall, *The German Energy Transition*, DOI 10.1007/978-3-662-54329-0_8

Concerning the renewable energy technologies of hydropower and biomass:

Hydropower Plants

Hydropower plants have been in use for decades (regardless of energy policy), i.e. as the only RE, they have always been an integral part of the electricity mix in Germany. However, years ago hydropower already—and here all the experts agree—essentially reached its natural limits of around 5 GW of output and 20–25 TWh per year (depending on weather conditions) of electricity production. It therefore has no role to play in the planned expansion of renewable energies and in the *Energiewende*.

Biomass Power Plants

Biomass power plants have been expanded from 1 GW in the year 2000 to almost 7 GW today. They now yield approximately 50 TWh of electricity per year, i.e. around 25% of current total RE electricity production and about 8% of the total electricity generated (excluding exports)[1].

Biomass power plants have a special role within the available renewable energy technologies. They employ the same basic principle as fossil fuel power plants: The fuel is burned and the energy released is converted first into steam and then into electricity. In other words, biomass plants are much like "normal" power plants, the only difference being that instead of using natural gas, coal or oil (i.e. biomass stored in the Earth's crust, formed millions of years ago) as fuel, they instead use biomass that has been produced recently or decades before. This means that biomass plants also emit CO_2, but in the exact amounts that have been sequestered from the atmosphere as the biomass has grown in the preceding years; hence, biomass power plants can be classed as carbon-neutral.

Accordingly, these power plants also have the same characteristics as conventional power plants: They are largely location independent, i.e. they can be built near consumption centres; they are available at all times; and they can be controlled to adapt to constantly fluctuating electricity consumption levels.

Therefore If it were possible to base a very substantial part of the *Energiewende*/ RE expansion on biomass power plants, the entire electrical infrastructure could remain largely unchanged. Specifically, the far-reaching systemic consequences of the *Energiewende* still to be described in this chapter would mostly not occur or would have only a moderate impact. Essentially the only change would be in substituting the fuel for the power plants.

However, this is not possible. The reason for this is simple: The fuel for biomass power plants—mainly biogas derived from corn, other agricultural products and wood—has to be produced in Germany, and the necessary land is simply not available.

If, for example, 500 TWh of electricity (i.e. about 80% of the gross electricity consumption in Germany) were to be produced from biogas, it would require an acreage of more than 20 mio hectares (100 hectares = 1 km^2, 259 hectares = 1 square mile); however, the total agricultural acreage in Germany is only 17 mio hectares.

Table 8.1 Use of arable land in Germany

	Millions of hectares	%
Feedstuffs	9.5	57
Food	4.6	27
Energy crops for biogas	1.3	8
Other	1.3	8
Total	**16.7**	**100**

2013 figures; [2]

Approximately 1.3 mio hectares of arable land is required to produce the current level of around 30 TWh of electricity from biogas, which is nearly 8% of the available land in Germany. A further 5% is used for biofuels (see Table 8.1). Increasing this would be difficult, and consequently the "Lead Study 2011" plans only a very modest additional increase in electricity production from biomass from now onwards.

The same also largely applies to solid biomass, i.e. wood. Even now about 50% of timber production in Germany is already used for energy, where use for space heating dominates over use for electricity production.

Of course, one could ask whether it might not be feasible to import biomass fuels. But, firstly, that would thwart the *Energiewende* motive to reduce dependence on energy imports, and, secondly, such an approach would not be economically viable. In any case, biomass has been by far the most expensive RE technology for several years.

Conclusion Biomass has played a significant role in the progress of the *Energiewende so far* and it has attractive properties, but when it comes to the *future of the Energiewende* in Germany, it cannot provide a major contribution.

> From a purely conceptual perspective, one can establish that Germany essentially depends on wind and solar power, i.e. on wind turbines (onshore and offshore) and PV plants, for the expansion of renewable energies in electricity generation.

This simple statement has far-reaching consequences, namely, the systemic consequences of the *Energiewende* that will be illustrated in the following sections.

8.2 Types of Renewable Energy 2

So far in the *Energiewende*, solar and wind power have clearly dominated the expansion of RE. Looking at the renewable energy plants built between 2000 and 2015, wind (onshore) and solar account for more than 90% of the power output and almost 70% of the electricity produced. Offshore wind power, by contrast, has not yet played a major role. We have also just seen that when it comes to the future of renewable energies in Germany, from today's perspective, only solar power and wind power are still available.

However, what will the mutual relationship between the three renewable energy technologies look like in the future?

– Wind (onshore) = wind (on)
– Wind (offshore) = wind (off)
– PV

Would it be useful, for example, to focus on one or two of the three? Furthermore, would it possibly have made more sense previously in the course of expanding RE in Germany, e.g. to build only wind turbines?

To answer this question, let us consider the essential characteristics of the two previous pillars of the *Energiewende*, PV and wind (on), in more detail:

– Both are available in sufficient quantities. Just 2–3% of the surface area of Germany is sufficient to completely supply Germany with PV electricity; wind (on) requires even less.
– Both are heavily location dependent: "in the big picture", i.e. in terms of geographical location in Germany, and "in the small picture", i.e. in terms of the immediate vicinity (shade, wind cover, etc.).
– Both cannot be controlled in terms of power output over time, i.e. electricity production depends entirely on local weather conditions. In other words, an installed capacity of 1 MW means the actual power output available will vary between 0 and 1 MW.
– Both are also highly volatile: The available power output and thus the electricity produced by the plant can vary greatly within short amount of time—within the space of an hour or in extreme cases a quarter of an hour.
– Both are *currently* comparable in terms of cost (when operated in Germany): Today the total cost per kilowatt-hour of electricity is €0.06–0.08 for PV and likewise € 0.06–0.08 for wind (on).

  (However, this was not always the case. In 2005, for example, PV electricity was still about three times as expensive as wind (on) electricity, and in the future the development of the cost could also be quite different.)
– Finally, both PV and wind plants are pure fixed-cost systems. The investment costs for both systems are high, but once they are built, it costs nothing to produce a kilowatt-hour. This is in contrast to conventional power plants (or biomass power plants) in which the fuel cost (i.e. the cost to produce a single kilowatt-hour at an existing plant) plays a significant role.

Conclusion
In terms of the core technical parameters as well as the key economic parameters, the two dominant renewable technologies at this time, PV and wind (on), are quite similar.

Given this conclusion, we must now repose the original question: Would it possibly have been wiser to rely on only one of these two technologies in the *Energiewende* so far?

The answer would seem to be a clear no. It was, and for the foreseeable future will be, the right decision to implement the *Energiewende* based on *two* pillars. The main reasons for this are as follows:

- In 2005 or 2010, it was not possible, or was only partly possible, to predict how both the technologies and the costs of the two RE types would evolve. Even today it is very difficult to predict the potential technological development prospects for PV and wind power and above all what the costs of these technologies will look like in 2030 or even in 2050. The ability to spread the risk was sufficient reason to work on and use both technologies in Germany.
- Both electricity sources complement each other fairly well, both in *geographic terms*—the best conditions for wind power are mostly found in the north of Germany, for PV in the south—and in *temporal terms*: PV delivers high production rates at noon and in summer, wind power in winter and evenly throughout the day. In other words, the weather-related geographical and temporal variations in electricity production average out much better in a combined PV/wind system than in a PV-only or wind-only system.

However, even if these considerations lead us to a clear conclusion, the issue of what role should be played by offshore wind power remains to be answered. Is it required as a third pillar in the future electricity system?

No, a third pillar is obviously not required in the strict sense. The above figures for PV and wind (on) clearly show that they alone are sufficient to provide the 430 TWh per year of electricity supply that is needed in terms of domestic RE according to the Lead Study 2011 [3] for 2050. Nevertheless, the wind (off) technology plays an important role in this planning: It is projected in [3] that wind (off) will produce around 130 TWh of electricity per year in 2050, i.e. the same volume as wind (on). The potential of wind (off) technology in Germany is also significant: Around 8% of the North Sea area available to Germany will have to be utilized to produce the projected 130 TWh per year.

The primary reason for the consideration of wind (off) technology in the implementation plan of the *Energiewende* is that, despite a number of fundamentally similar characteristics—weather dependency, volatility and a fixed-cost system—it has a significant advantage over PV and wind (on): It is clearly more reliable and constantly available.

For a number of years it looked like this advantage would have to be traded off against significantly higher overall cost per kilowatt-hour. But recent technological advances and drastic cost reductions indicate that wind (off)-costs are actually already in a range similar to wind (on) and PV. This means that (as of today) it indeed makes sense to rely on all three technologies for the forseeable future of the *Energiewende*.

Conclusion

Due to the restricted availability of hydropower and biomass in Germany, in the future the *Energiewende* will have to rely on both of the technologies that already dominate the renewable energy sector, PV and wind (on), as well as on the wind (off) technology.

We should emphasize that the question concerning the optimum ratio of PV to wind (on) to wind (off) in the future is still open at this point. This issue is, and will have to be, largely dependent on how—certainly also in mutual competition between them—the three technologies evolve in the coming decades, especially on the economical side.

To give a more vivid example: It is perfectly conceivable that a 70:30 ratio of PV to wind will turn out to be optimal; and it is just as possible that a ratio of 30:70 will be the best solution in terms of cost-efficiency. In other words, we might see 100 TWh of PV electricity in 2050, but we might also see 200 TWh of PV electricity (or more). *From a purely technical perspective, both scenarios are clearly feasible*.

8.3 Grid Expansion: The Spatial Dimension

The conclusion we can draw based on the preceding sections is that solar and wind (on) must be two central pillars of the *Energiewende* in Germany. We have already demonstrated that both technologies have one thing in common: Electricity production depends greatly on geographic location, "in the big picture" (in the north or south of Germany) and "in the small picture" (the choice of site in a specific region).

However, wind intensity and solar irradiation available in a location, i.e. the quality of the site for a renewable power plant, logically have no bearing on the proximity of this site to any major centres of electricity consumption. A location that is ideal for generating electricity in terms of wind or solar intensity will generally not be the place with the highest demand for energy.

In the big picture, centres of electricity consumption tend to be located in the south and centre rather than in the north of Germany. In the small picture, they are more often found in urban than in rural areas. The southern German states (Bavaria, Baden-Württemberg, Rhineland-Palatinate and Saarland) have a combined electricity consumption of approximately 220 TWh per year, while the northern states (Lower Saxony, Schleswig-Holstein, Mecklenburg-Western Pomerania, Brandenburg, Saxony-Anhalt, Bremen, Hamburg and Berlin) together consume around 140 TWh per year, i.e. only about 65% as much (Table 8.2).

This creates a conceptual issue with respect to the implementation of the *Energiewende*, which existed, if at all, to only a very limited extent for conventional power plants:

– Either the choice of location for the construction of RE plants is based largely on the criterion of "Where is the electricity most needed?" as was previously the case for conventional power plants
– Or the choice of location is based primarily on the criterion of "Where is the electricity yield highest?"

It is obvious that this alternative is irrelevant with respect to the targets and motives of the *Energiewende*. And if we consider high security of supply to be mandatory, the choice between the two alternatives must be made primarily on the basis of the framework condition "affordability/cost-efficiency".

Hence the More Focused Question Is Is it cheaper in terms of macroeconomic cost to select locations for RE plants according to the criterion of maximum electricity production and then to build additional power grids to connect these plants to geographical centres of electricity consumption? Or is it economically more advantageous to locate RE plants as close as possible to consumption centres, i.e. to accept losses in electricity production per megawatt of installed capacity in return for eliminating the need to construct additional power grids (at least to a substantial extent)?

Table 8.2 Electricity consumption by region in Germany (in TWh) in 2015

Region	(Gross) electricity consumption
North	140
Centre	235
South	220
Total	**595**

Various sources on the electricity consumption of the German states, own calculations

With respect to wind (on), the following facts will be helpful in answering this question:

– The wind speed in southern Germany is on average at least 40% less than in northern Germany, especially in coastal regions. Therefore, the electricity yield of a 1 MW wind plant in the north is on average around 2.5–3 times higher than in the south. If wind electricity costs €0.06–0.07 per kWh in coastal areas, the average cost in the south is more than double. Put another way: Even as little as a 10% drop in wind speed will, all else being equal, increase the price of electricity by at least 35%, i.e. by at least €0.02 per kWh.
– Transporting 1 kWh of electricity from the north to the south of Germany—with new overhead power lines to be built—will cost €0.01–0.015 [4].

These few figures clearly imply that, generally speaking, it is indeed more expedient, because it is significantly cheaper, to produce wind (on) electricity where wind conditions are good—i.e. mainly in northern Germany—and then transport it via newly built power grids to the south, than it is to build wind (on) farms mainly in southern Germany, i.e. close to centres of consumption.

And this is exactly how the expansion of wind (on) energy actually proceeded so far. Currently 70% of wind (on) electricity is produced in northern Germany, with the remaining 30% is generated across the rest of the country [5].

In this context, let us address four further aspects:

1. The figures also show that wind (off) technology cannot be eliminated from Germany's future energy mix solely for the reason that it is very away from the consumption centres. Of course, this is a cost disadvantage. However, if the cost of wind (off) technology itself continues to develop positively, then this disadvantage will be offset quickly.
2. When it comes to PV technology, the relevant figures do not suggest a clear direction. PV electricity in southern Germany is on average 10–20% cheaper than it is in the north. However, since geographical and utilization aspects do point in the same direction for PV, in practice this does not play a similar role.
3. Concerning the relationship between urban and rural regions, without going into detail for reasons of space, we can draw similar conclusions. Expanding the distribution grid is likewise cheaper than accepting major compromises in the choice of locations with respect to optimal electricity production.
4. In the most likely scenario of future RE expansion at this time, we can expect a RE production of around 180 TWh per year in northern Germany in 2030, in contrast to an electricity consumption of only 140 TWh per year in northern Germany. From this consideration alone, it is inevitable to transport large quantities of electricity from the north to the south as part of the *Energiewende*.

Conclusion

In terms of macroeconomic cost, it is clearly more sensible to produce wind (on) electricity mainly in the north of Germany and then transport it to southern Germany than it is to build the required wind turbines mainly in the south near the centres of consumption there (which would of course be possible from a purely technical perspective).

Therefore, and also due to the significant role of wind (off) in the RE expansion, it is an essential systemic consequence of the *Energiewende* that new transmission grids will be needed in Germany to a considerable extent.

These considerations become more complex if—as happened in Germany in the summer of 2015—demands are presented and decisions are made that new transmission grids must be built primarily in the form of *underground* power lines. We will address this topic in the second part of the book (Sect. 14.2).

8.4 Volatility: The Temporal Dimension

PV and wind electricity are now, and will continue to be, the main pillars of the *Energiewende* in Germany, that much is certain. In addition to electricity production being dependent on location as discussed in the previous section, these technologies have one other obvious common feature: Electricity production at these plants is completely dependent on the weather and thus on point in time. Production varies greatly over time and there is no way it can be influenced. For an individual plant—no matter where in Germany it is located—this is obvious: The usable power output fluctuates constantly, often within a day but, in any case, within the space of a week, between 0 and 100% of the installed capacity. However, the following is also true for Germany as a whole: Although PV and wind (on) plants with an *installed capacity* of 80 GW are now in operation in Germany—which is nearly the same power output as all its conventional power plants combined—over the course of a year, the *usable power output* of these RE plants together fluctuates between 0 and around 70% of the installed capacity, i.e. between 0 and 55 GW. The average power output over the entire year is only about 15% of the installed capacity, i.e. currently about 13 GW.

In other words, from 1 GW of installed PV capacity, Germany currently gets no more than about 1 TWh electricity per year; 1 GW of installed wind (on) capacity can produce about 1.7 TWh per year in Germany. Compare this to 7–8 TWh per year in electricity from 1 GW of nuclear or 1 GW of lignite-fired capacity.

These few figures have very far-reaching consequences if—as is the overarching goal of the *Energiewende*—an electricity system is to be built largely on renewable energy, which for Germany essentially means solar and wind power.

8.4.1 Three Consequences

1. It takes a lot of installed capacity to generate relatively small quantities of electricity. Generating 330 TWh per year from PV and wind in 2050 would require at least 160 GW of installed capacity ([3], scenario 2011A). However, the average power output required in Germany is only about 60–65 GW, and the maximum power output required (on cold winter days) is 80–85 GW. This means there will be many hours over the course of a year during which the installed PV and wind plants alone produce too much electricity, i.e. electricity that is not needed by electricity consumers in Germany at that time. How to deal with this?
2. Conversely, despite an enormous installed capacity of 160 GW (for comparison: in 2000, before the *Energiewende*, conventional power plants in Germany provided only around 100 GW installed capacity), there will be many hours over the course of a year during which these plants produce much too little to cover the electricity demand in Germany at that time. How to deal with this?
3. Another significant consequence—one which we will not discuss in detail in this book—is the large, uncontrollable fluctuation in power output within short periods of time. If a windy, sunny day is followed by a windless dusk, power output can change by 50 GW or more in the space of just a few hours. This situation was unthinkable only 10 years ago, and the energy companies' conventional technical control systems are not designed to cope. Solutions must be found to these challenges as well.

   Nevertheless, let us focus on items 1 and 2. In short, the (weather dependent, i.e. uncontrollable) *production of electricity* does not match the *demand for electricity* at all. This is in stark contrast to the former electricity system in Germany. The conventional power plants were built and operated every day (i.e. powered up and shut down) such that the demand for electricity was covered exactly at every point in time.

Preliminary Conclusion
The *Energiewende* is not just about simply replacing certain types of power plants with other types of power plants, but rather involves a much more fundamental redesign of the entire electricity system.

8.4.2 Five Options

So how can this challenge be tackled? In principle, i.e. from today's purely technical-conceptual perspective, there appear to be *five options* for Germany:

1. Switch off RE plants
The easiest approach, of course, would be to simply *shut down* some of the RE plants when excess quantities of electricity are generated by PV and wind, i.e. to "discard" the energy available. When too little electricity is generated by PV and wind, the shortfall can be generated in conventional power plants (although this would require maintaining large parts of today's conventional power plant fleet in the long term).

2. Exchange Electricity with Neighbouring Countries
A second option is to increase the *exchange of electricity with neighbouring countries*. Importing and exporting electricity would at least partly offset any over- and underproduction (corresponding willingness and technical possibilities in the neighbouring countries provided, of course).

3. Control the Electricity Demand
The third option is based on a different approach. So far in the electricity system, the demand from electricity consumers in Germany has always been accepted as a given, and electricity production has been controlled to meet this demand. However, this need not always be the case. There are reasonable ways to also control electricity demand—at least to some extent. Of course, this should be done in a way that does not affect comfort in private homes to a large degree and does not impair industrial performance.

Measures of this type used to control the demand for electricity are commonly referred to as demand-side management (DSM).

4. Store Electricity
The fourth, and in some ways perhaps the most obvious, means of tackling this challenge consists in electricity storage systems. If too much electricity is generated from PV and wind power, it can be stored and then made available again when required, i.e. under conditions of little electricity generation.

This is the principle behind the entire German natural gas industry. Vast underground storage facilities are used to bring the largely constant flow of natural gas from the producing countries Russia, Norway and the Netherlands in line with demand, which varies widely over the course of the year (high gas consumption in winter, low gas consumption in summer).

This obvious solution confronts, however, one fundamental problem insufficiently solved so far: It is technically difficult and it is still expensive to store significant quantities of electricity—which leads us to one of the central themes of the *Energiewende*:

"Can we solve the storage problem at a reasonable cost?" This question has been the subject of much controversial debate in recent years.

5. Install Additional Electricity Consumers/Promote Sector Coupling
Finally, there is a fifth way to solve in particular the problem of temporary overproduction: installing *additional* (i.e. structurally not yet existing) *useful electricity consumption systems*, which comprise variable control systems to allow for activation and deactivation whenever electricity production from RE exceeds the current demands of existing electricity consumers. What might such "additional useful electricity consumption systems" look like? Facilities for generating heat (and thus replacing fossil fuels in space heating), plants for producing hydrogen (as fuel for cars thus replacing fossil fuels in transportation) and so on. This would simultaneously create links between the hitherto largely separate energy sectors of electricity, heat and transportation and the so-called sector coupling.

In conclusion, then, there are five options for solving the core problem of the RE technologies PV and wind, that is to say, their complete weather dependence and thus massive yet uncontrollable temporal fluctuations in power output.

8.4.3 Which Is the Best Option?

First, some important notes:

– Looking at the different options, it is clear that none of the options preclude any other. They are all mutually compatible and can be combined.
– Since they all support the targets and motives of the *Energiewende* in the same way, the choice from among these options must be based on compatibility with the framework conditions, i.e. in particular on the criterion of finding the most cost-efficient solution.
– While options 1 and 4 might be capable of solving the matter of fluctuating renewable electricity production alone, this is not possible with option 2 and realistically not with options 3 and 5 either, although the latter do have significant contributions to make.
– The ongoing global expansion of renewable energies entails that in many research institutions and companies around the world, the issue of electricity storage is being intensely worked on. Due to this, it is generally expected that

there will be very significant progress in storage within the next 10–20 years, on the technological side and especially on the cost side.
– Studies on this subject have consistently shown that up to a RE share of around 50% of the total electricity generated—i.e., according to the road map of the *Energiewende*, up to about 2030—the problem can largely be solved by adopting option 1, and up to that point, it is quite clearly the most cost-efficient option at a macroeconomic level.
– Finally, we can make the following highly qualitative, yet quite reliable, statement: Current estimates suggest that every option comes with a nonlinear cost curve, i.e. the greater impact we require an option to have, the more the (absolute but also the) specific costs will rise.

We could now go into detail regarding the advantages and disadvantages, current cost estimates, etc. for these options. However, this would only ever be a snapshot, since due to technological progress the situation might well be very different in 5 years' time.

We Can Therefore Say, in General Terms Only It makes sense for Germany:

– To rely primarily on option 1 for the next 10–15 years (since periods of significant over- or underproduction will still be very limited in this period)
– To use this time to develop storage technologies, DSM options, sector coupling technologies and grid interconnections within the EU as far as possible
– And then between 2030 and 2035 to decide, or ideally *let the market decide*, the extent to which each option can or has to be used to safeguard the balance between electricity production and electricity demand as the share of RE in the system increases further (and as conventional power plants are gradually decommissioned due to their age). In particular, it should then emerge
  • How many gigawatts of conventional power plants will be needed by 2040 and 2050
  • How many gigawatts of (additional) exports/imports can be contracted and reliably transported
  • Which DSM measures are economically expedient in the long term
  • To what extent additional electricity consumption facilities for heating and for transportation applications can be installed at reasonable cost and so excess CO_2-free electricity be used in other energy sectors as well
  • How many terawatt-hours of storage capacity are required for the *Energiewende* in the future and what technologies—possibly including storage available in neighbouring countries—are most cost-efficient to this end.

Although it is impossible to confirm today, it is probable that after 2030 a mix of all five options will be the most cost-efficient (while safeguarding security of supply) solution.

8.4.4 What Does this Mean for Germany's Electricity System?

In concrete terms, with regard to the systemic consequences of the *Energiewende*, this means (from today's perspective):

– Despite an expansion in RE plants from around 100 GW (2015) to at least 150 GW in 2030 and at least 180 GW by 2050 (with maximum power demand in Germany currently at about 80 GW), conventional power plants will be still required to a considerable extent: in 2030 around 60–70 GW (of about 90 GW today) and in 2050 probably still between 30 and 50 GW.

  In other words, to a considerable extent, conventional power plants will not be replaced by RE power plants, but the *Energiewende requires two power plant systems*: a conventional power plant system (needed to cover the hours during which too little RE electricity is produced despite enormous installed RE capacity) and a RE power plant system.
– In the years 2030–2050, to a significant extent, electricity storage systems as well as additional, variable-use facilities for converting electricity into heat and transportation energy and/or additional electricity exchange options with neighbouring countries will be required to be able to rationally use the electricity produced that exceeds (conventional) demand during many hours of the year.
– In the future—starting in the next decade, then more intensively from around 2030/2035 on—the *Energiewende* is likely to produce complex interactions between a variety of modules, starting with the volatile electricity production from PV and wind plants: fast powering up and shutting down of conventional power plants; use of various types of electricity storage systems; export and import of substantial quantities of electricity; and use of facilities to control the demand for electricity by starting and stopping industrial production plants, heat pumps, night storage heaters; facilities for hydrogen production and so on.

  It is obvious that this will require sophisticated, highly automated control systems. **Therefore, the increasing digitization of the economy in general will play a central role in the energy economy as well.**

Conclusion

– The characteristic shared by PV and wind plants of temporal variations in electricity production will give rise to a significantly broader energy infrastructure in the course of the *Energiewende*. Instead of *one* fleet of conventional power plants, there will have to be *three* different fleets: RE plants, conventional power plants and storage facilities.
– It will also be necessary to intelligently control these three fleets, along with numerous electricity consumers' devices and also new power lines to neighbouring countries, so that in any weather and in any RE electricity production situation, an economical optimum is provided while respecting the primacy of security of supply.

8.5 Fragmentation of the Energy Landscape

The conventional power plant fleet (nuclear, lignite, hard coal and natural gas), which previously dominated electricity production in Germany before the *Energiewende* by more than 90%, was (and is) of a simple structure. There are only a few hundred power plants with a typical installed capacity of 300–1000 MW (0.3–1 GW) and a typical electricity production of 1–10 TWh per year; these are *large-scale complex industrial plants*. The reasons for this are quickly enumerated: vast economies of scale (a small CHP block costs more than five times as much per installed kW as a large-scale power plant), better physical properties and better cleaning of exhaust gases.

This characteristic also entails that only a few companies in Germany have (had) the required expertise and the necessary capital (typically €0.1–1 billion) to build and operate such plants. Despite its size, a typical conventional power plant has only a small footprint: The power plant itself is only about 0.1 km^2 in size, with ancillary facilities covering a maximum 1 km^2.

The RE plants are fundamentally different in this respect:

Economies of scale

The economy of scale is minimal: One wind turbine costs approximately the same (in terms of cost per installed MW) as 10 or 100 wind turbines in a wind farm. (The economy of scale is significant with regard to *individual* wind turbines, and here technological advances are indeed being made, though it seems difficult to achieve more than 3–4 MW per wind turbine (onshore), from today's perspective.) The same applies to PV modules.

Footprint

Renewable electricity generation demands an immense footprint compared to conventional power plants. A 1000 MW solar power plant would require 30 km^2, i.e. a field 5 km $\times$ 6 km in size. A 1000 MW wind power plant would have to extend over an area of more than 100 km^2; however, the fields in between the individual wind turbines can still be used for agricultural purposes. Technically and economically these scales are unobjectionable, but in a densely populated country such as Germany, such dimensions are impossible to realize.

(As we have already seen in Sect. 8.1, this applies to an even greater extent to biogas power plants. A 1000 MW biogas power plant would require acreage of more than 3000 km^2 around the plant.)

What Follows from This?

RE power plants are typically much smaller than conventional power plants, and they can really be small indeed without suffering any major cost-related or technical disadvantages: PV plants and biogas plants just a few hundred kW and wind turbines a few MW. Accordingly, the costs of such plants are typically

€1–50 million. (For even smaller plants—which are widespread in the PV sector in Germany—specific costs then increase significantly.)

In Other Words RE power plants are not large complex industrial facilities; rather this technology allows plants to be assembled in a few days or weeks from standard components, in a variety of sizes and without the need for overly complex expertise.

These completely different characteristics with respect to size, expertise and necessary capital have far-reaching consequences:

- Germany's energy landscape is becoming heavily fragmented due to the fast-growing population of RE plants. In lieu of a few hundred power plants, already thousands of wind farms, some 10,000 biogas plants and more than a million PV systems are installed.
- Construction of RE plants is not limited to a few companies, but can be planned, financed and implemented by many stakeholders.
- There is another completely different reason why this fragmentation and plurality of stakeholders are important: The RE plants built between 2000 and 2014 alone called for €170 billion in investments (see the third part of this book). It would have been very difficult for the incumbent energy industry to raise this sum: In the same period, the energy companies only invested €100 billion in the electricity sector, of which €50 billion was required just for the power grids.

  More tangibly: On the financing side alone, the *Energiewende* has only worked so far because the expansion of renewable energies can be split into relatively small parts and the respective necessary capital distributed across many shoulders—many investing stakeholders. (In fact, incumbent energy companies account for just 10–20% of investment in RE plants so far.)

Further Aspects

Let us conclude this section by briefly addressing a number of further aspects in this context.

- As we have seen, in the context of the *Energiewende*, the characteristics of PV and wind are systemically causing electricity generation in Germany to become much more fragmented and require support from many more stakeholders than before.

  Historically, this was almost a prerequisite for the *Energiewende* to take its recent, rapid course in Germany—not only because of the major investments needed. For a long time, until the end of the last decade, the established energy companies were sceptical about RE and thus very reluctant with respect to investing in RE plants, despite the good ROIs achievable. Other stakeholders were needed to advance the expansion of renewable energies, especially between 2000 and 2010.
- An important side effect of this development is that it automatically provides a solution to one of the main criticisms of Germany's former energy landscape: the "oligopoly" in German electricity generation. In fact, more than 80% of

conventional power plants were previously owned and operated by just four companies: E.ON, RWE, EnBW and Vattenfall. The extent to which the relevant criticism of these companies or of this state of affairs was justified or not, is a question beyond the scope of this book. However, it is important to note that **the *Energiewende* is systemically breaking up the "oligopoly of the Big Four", and for a significant part of the political and social spectrum in Germany, this is an additional motive for the *Energiewende*—in addition to and beyond the four motives of the *Energiewende* illustrated in this book.**
– The significantly larger footprint of RE plants compared to conventional power plants, as mentioned above, has its own implications that we will discuss in the next section.
– These considerations apply to the currently dominant technologies of PV and wind (on) as well as biomass. Wind (off) technology is more like conventional power plants in this respect. With typical installed capacities of 100–500 MW, investment volumes of €0.1–1 billion and more complex technical issues wind (off) plants can typically only be realized by large companies.

Conclusion
– Before the *Energiewende*, electricity generation was dominated by a few large-scale industrial plants and was therefore in the hands of a few major energy companies.
– Production of electricity from RE (onshore) in Germany is, by contrast, characterized by a very large number of plants of different capacities—the largest ones still being smaller than conventional power plants by a factor of ten—and by a variety of different companies and stakeholders that are capable of building, funding and operating these plants.
– The electricity system of the future is thus, at a technical level, a great deal more fragmented and, at an economic and social level, much more complex than it used to be.

8.6 Footprint, Physical Presence of Renewable Energies

As described in the previous section, RE plants have a much larger footprint than conventional power plants.

The, not unjustified, discussion in recent years in Germany about the immense use of land for biogas plants (currently approximately 5000 mi^2) and the topics involved therein—monocultures, "cornification" of the landscape and energy versus food production—will not be addressed here in more detail, firstly, because we can assume that the status quo has been largely accepted by now. Secondly, and more importantly, for cost reasons alone, biomass plants will (in all probability) not play a significant role in the further expansion of renewable energies in Germany. On the contrary, we might even see a gradual decline in biogas plants in favour of

PV and wind plants after 2025 (i.e. after the end of the respective 20-year GREA subsidization). In other words, the very large current footprint of biogas plants is not really a *systemic consequence* of the *Energiewende*—which can be implemented even without biogas plants—but a (presumably partly transitory) status due to *historical reasons*.

How Can We Assess the Issue of Footprint for the Future (Focusing on PV and Wind)?
Taking the target state as planned for 2050, let us assume that around 60–70 GW of wind turbines will be installed onshore and about 70 GW of PV systems (of which about 50% on roofs, i.e. that do not need additional land). Ground-mounted PV systems will then occupy a maximum area of approx. 1000 km^2. The 60–70 GW of wind turbines in wind farms, each comprising 2–20 turbines, will cover a total area of approximately 2000–3000 km^2, of which the turbines themselves would actually only utilize a maximum 200 km^2, i.e. the remaining areas can continue to be used agriculturally.

Looking at these figures, we need to distinguish between three aspects:

– The actual use of land by RE plants is near negligible ($<$1500 km^2), approximately 0.4% of Germany.
– The footprint of the RE plants (not including biogas plants) is indeed higher, 3000–4000 km^2, but still accounts only about one percent of Germany's land area. It is therefore not of a magnitude that should constitute a serious obstacle to the *Energiewende*.

  We note in this context that currently 2000–3000 km^2 of land has been claimed for opencast lignite mining, which will no longer be the case in the target state in 2050. **Therefore the land balance between the previous and the new electricity system is largely offset.**
– There is a more critical question in relation to the indirect effects. While large PV plants are less conspicuous (also due to their location along traffic routes), largely uncontroversial and expected to remain so, the 2000–4000 wind farms to be installed in Germany by 2050 will in many places become an integral part of German landscapes that cannot be overlooked, and they will have noticeable impacts on the immediate surroundings. This applies, of course, mainly to northern Germany and in particular its coastal regions.

8.7 Consequences for Conventional Power Plants

We have seen in the preceding sections that the characteristics of the main pillars of the German energy transition—PV and wind—will inevitably create a situation in which, despite the extensive construction of new RE plants in the course of the *Energiewende*, conventional power plants will still be needed to a significant extent in the future.

Table 8.3 Conventional power plant fleet in Germany

	2000	2010	2015 (actual)	2030 (planned)	2050 (planned)
Capacity (GW)	100	100	90	60	35
Electricity production (TWh)	540	510	405	250	80
+ Export (TWh)	0	18	52	(Pending)	(Pending)

[1, 3, 6]

Let us reconsider this in numbers ([3], scenario 2011A, 2030 adapted to the German government's current plans) in Table 8.3.

What do these figures mean?

- Aside from the forced shutdown of around 8 GW of nuclear power in 2011, the size of the conventional power plant fleet has remained virtually unchanged in the last 15 years. Large parts (about 70%) of the current fleet will still be needed until at least 2030.
- The utilization of these power plants has barely decreased. Adjusted for exports (i.e. to cover the electricity demand in Germany), the hours of use did go down: In 2015, these conventional power plants produced 75% of the electricity they delivered in 2000 with an installed capacity of about 90%. However, this effect was largely offset by increased exports of electricity. Per gigawatt of installed conventional capacity, almost the same amount of electricity was produced in 2015 as was in 2000 (about 5 TWh per GW).
- However, this rate will drop (excluding electricity exports) to approximately 4 TWh per GW by 2030, and in the decades that follow, in line with the concept of the *Energiewende*, conventional power plants will increasingly serve merely as backups, i.e. to be started up only when at least 180 GW of installed RE capacity—together with RE electricity imports and storage facilities—are not sufficient to cover domestic demand at that time.

According to Germany's current market rules, power plants earn their money exclusively from the amount of electricity they produce. In light of these figures, the question arises as to whether an annual production of 3 TWh or even just 2 TWh per GW (rather than today's 5 TWh per GW) will be sufficient to operate these power plants profitably in a market economy.

Conceptually speaking there are two basic alternatives with respect to this issue:

- Either conventional power plants will have to earn on average significantly more money per kilowatt-hour in the future than they do today
- Or the market rules must be modified such that conventional power plants are paid not only for producing electricity but also for providing guaranteed power output, in other words, for the backup function they perform in the future electricity system.

The choice between these two options *must* be made if the framework condition "market economy in electricity generation" is to be fulfilled. In particular, it must be done in such a way that even in the coming decades, there will be companies willing to operate or invest in conventional power plants.

Failure to do so, i.e. if conventional power plants are not available in the required capacity the obvious consequence will be that, during weather conditions of little wind and little sunlight, Germany's security of supply could not be maintained.

Conclusion

A systemic consequence of the expansion of RE in conjunction with the framework conditions of "security of supply" and "market economy" is that the market rules for conventional power plants need to be designed such that, even in the long term—i.e. with much less annual hours of use—these power plants can be operated profitably in the market to the extent required.

We can further refine these considerations on the basis of the specific conventional power plant fleet in Germany. In the years 2000–2010, when RE had no significant impact on the electricity market yet, power plants in Germany were essentially ranked in order of merit (= deployment order) as illustrated in Table 8.4.

The two power plant types "highest up" in the merit order, i.e. those with the highest variable costs (= cost of producing a kilowatt-hour at an existing power plant, excluding fixed costs for construction and operation), were natural gas and hard coal.

Due to the way the market operates, the variable costs of these two types of power plants thus also *determined the price on the German power exchange (EEX)*, namely, with an approximate ratio of one-third gas to two-thirds hard coal (based on annual hours of use of around 3000 for gas-fired power plants).

The PV and wind plants have variable costs of 0, which means that they rank *at the bottom* of this merit order, gradually driving out the power plants from the market that rank higher in the merit order. There are fewer and fewer hours during which the power plants high up in the merit order are needed to cover electricity consumption in Germany, i.e. are actually being utilized. **In this way, first the**

Table 8.4 Merit order of conventional power plants in Germany, 2000–2010 (in GW; rounded)

Capacity (GW)	Type of power plant
15	Natural gas (excluding CHP)
25	Hard coal (excluding CHP)
22	Lignite
15	CHP (natural gas, hard coal)
20	Nuclear power
5	Water

CHP = cogeneration, i.e. joint production of electricity and heat; [6]

gas-fired power plants are ousted from the market in Germany (except for CHP plants) followed by the hard coal-fired power plants.

From a systemic point of view, this inevitable effect, i.e. this impact automatically created by the *Energiewende* in conjunction with the current market rules in electricity generation, has two major consequences:

– One consequence has already been mentioned: conventional power plants, in particular the gas- and hard coal-fired power plants, are being utilized less and less, bringing their economic viability into question.

  Since these power plants will still be needed for some hours (albeit for far fewer hours than before) to ensure security of supply, complying with the framework condition "market economy" entails that market rules must be (re) designed to guarantee profitability.

– The second consequence is as follows: As the most expensive power plants in terms of variable cost are gradually ousted from the market, their influence on the price decreases—with the logical consequence that the average electricity price on the EEX drops.

In other words:
The expansion of RE necessarily leads to decreasing electricity prices on the energy exchange and thus—because current market rules are such that all power plants earn their money (only) via these prices—falling profitability for all conventional power plants.

Put more tangibly: It is inevitable that in the course of the *Energiewende*—at least with the market rules as they stand today—operators of conventional power plants will see profits decrease.

8.8 Systemic Consequences: Conclusion

Let us summarize the main findings of this chapter.

If the aim is to achieve the three targets of the *Energiewende*, to satisfy the four underlying motives and to simultaneously comply with the three framework conditions, this will inevitably entail a number of significant systemic consequences for the German electricity system in the future. That is, essential characteristics of Germany's future energy landscape are predetermined:

– In the foreseeable future, Germany will have to rely on **sun power and wind power** for the RE expansion in the course of the *Energiewende*; there will be hundreds of offshore wind parks, thousands of onshore wind farms and an even much greater number of PV systems.

– The power grid will have to be considerably expanded; in particular, there will be large **new transmission power lines**, especially from the north to the south of Germany.
– In addition to the vast number of RE power plants and to the conventional power plants (which will then be online for only relatively a few hours per year), there will be a significant volume of **additional technical infrastructure** to manage the temporal fluctuations in PV and wind (on) electricity: large-scale energy storage and small-scale energy storage in private homes; control elements for managing electricity-consuming equipment and devices in industry, and possibly also in private homes; additional power lines to neighbouring countries to capture synergies with their electricity systems; and new facilities that convert electricity into forms of energy that are then available for space heating and transportation purposes (i.e. capturing synergies between the three energy sectors).
– A **digital infrastructure** is superimposed over this that controls the complex interplay between the various infrastructure components.
– These numerous facilities gradually replacing the relatively few conventional power plants will drastically increase the **visually perceptible physical presence of the electricity infrastructure** and thus the number of citizens directly affected by this infrastructure.
– Due to this fragmentation as well as the high investment needs, the *Energiewende* brings with it a development in electricity generation according to which the relevant infrastructure is no longer built, financed and operated by only a few large energy companies, but by a **variety of different stakeholders**. As a result, the economic interests and stakes in relation to the implementation of the *Energiewende* are likewise distributed across a variety of businesses, citizens and institutions.
– The *Energiewende* leads to an ousting from the market of those conventional power plants that are most expensive in terms of the related variable costs—e.g. gas-fired power plants initially then the hard coal-fired power plants—thus to **decreasing electricity prices on the energy exchange** and consequently to decreasing profitability of conventional power plants overall. Further development of the market rules is needed in the longer term to adequately map the gradually changing function of conventional power plants.

The *Energiewende* inevitably entails that the electricity system in Germany becomes much more infrastructure intensive, complex, fragmented, decentralized, capital intensive, as well as distributed between a much larger number of stakeholders than before.

We can assume today with great certainty that an electricity system like this can be *technically* mastered. The real question that springs to mind, however, is how such an energy economy can be *politically* controlled. For although the above-mentioned contours of the future energy landscape in Germany are largely predetermined, there will always be several technical alternatives within these contours. There will always be a multitude of concrete options for how to shape the ongoing implementation of the *Energiewende* and, in particular, how to organize and regulate a market for electricity infrastructure that (rather than a public authority) is expected to govern future developments as far as possible.

The extent of grid expansion, the size and type of storage facilities, the extent and nature of the remaining conventional power plant fleet, small-scale versus large-scale technologies, decentralized elements versus central elements, and many other aspects—these open questions constitute indeed a vast number of available conceptual/technological alternatives within the *Energiewende*. These options will differ in terms of current and future costs, the degree of visual presence and direct impact on citizens and the degree of autonomy awarded to individual regions versus dependence on larger entities. In short, they will differ with respect to a wide variety of interests among many stakeholders.

Political decisions in this arena will necessarily affect a multitude of interests and inevitably favour some interests over others (or at least that will be the perception). Handling all this consistently within a democratic process over several decades—in such a manner that the requisite underlying social consensus on the *Energiewende* is not jeopardized—is probably the most important challenge facing German society as regards the *Energiewende*.

References

1. AGEB (2016) Stromerzeugung nach Energieträgern 1990–2016. http://www.ag-energiebilanzen.de
2. BdEW (2015) Bio-Erdgas: Fragen, Antworten und Argumente. http://www.bdew.de
3. Leadstudy 2011. Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland, 29 Mar 2012. http://www.dlr.de/dlr/Portaldata/1/Resources/bilder/portal/portal_2012_1/leitstudie2011_bf.pdf
4. Unnerstall (2016) Faktencheck Energiewende. Springer, Berlin, pp 79/80
5. BdEW (2016) Erneuerbare Energien und das EEG: Zahlen, Daten, Grafiken (2016). http://www.bdew.de
6. Fraunhofer ISE. Energy Charts. https://www.energy-charts.de