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Causes and effects of the German energy transition in the context of environmental, societal, political, technological, and economic developments

Kai Kappner[1*], Peter Letmathe[1] and Philipp Weidinger[1]

Abstract

Background As lignite mining protests and #FridaysForFuture demonstrations gained momentum in Germany and further protests have been developing over time, this paper investigates the various causes and effects of the country's energy transition. Society and politics alongside economic, environmental, and technological developments have led to a profound and continuous transformation of the energy system, a transformation which is remarkable in terms of reach and speed for an economy of the size of Germany's. Pressure to transform the country's entire energy system even faster has recently been levelled due to the Russian invasion of Ukraine.

Results From the perspective of the different pillars of sustainability and various stakeholder groups, this paper discusses the influences and their interdependencies towards the status quo of the German energy sector. We have used the cause-and-effect analysis method to answer the question of why major energy generators in Germany are still struggling with the energy transition, as well as the question of why a strategy towards more sustainability is needed to maintain Germany's industrial strength in the long run. We found that energy transition in Germany is substantially driven by society, which pushes political decisions that lead to an economic transition, while environmental incidents are only triggers for further societal and political doings. Furthermore, technological developments fulfil only needs and do not necessarily hurry ahead of time.

Conclusions Overall, the article creates a profound understanding of the factors influencing the German energy transition which is deeply embedded in the European energy system.

Keywords Sustainability, Renewable energy, CSR, Energy transition, Cause-and-effect analysis

Background

The long-term development of the transition of the German energy system is of utmost importance for Europe, as Germany has the largest economy on the continent. Likewise, the various influencing factors identified in this paper and their interplay provide examples of how energy systems change in the long term and how companies can adapt to them at an early stage. These developments are important not only because of Germany's integration into the pan-European energy system, but also because Germany is a key political actor in the European Union and plays a decisive role in determining which trajectories are chosen in response to past, present, and future political events such as Russia's current invasion of Ukraine. A deep understanding of the German energy transition can,

*Correspondence:
Kai Kappner
kappner@controlling.rwth-aachen.de
[1] Chair of Management Accounting, Faculty of Business and Economics, RWTH Aachen University, Templergraben 64, 52062 Aachen, Germany

therefore, help to better assess current and future developments and the associated technological, ecological, economic and social consequences in other countries and the European Union as a whole.

Germany is internationally considered to be a pioneer in the transition of its energy system towards an increasing share of renewable energy sources [1–3]. Years ago, the then chancellor, Angela Merkel, was actually regarded as the "climate chancellor" [4]. Today, however, Germany has fallen somewhat behind by international standards and only reached rank 16 of the Climate Change Performance Index (CCPI) in 2023 after rank 13 in 2022 [5]. In 2020, the target of a 40% reduction in GHG emissions compared to 1990 was only just achieved, and that was just because of the consequences of the COVID-19 crisis, in particular due to significant reductions in the transportation sector [6]. The achievement of the targeted 65% (formerly 55%) reduction by 2030 is so far uncertain [7].

In Germany, currently 489 g of CO_2 are emitted on average during the generation of one kWh of electrical energy and, hence, a way has to be found to decrease carbon emissions and to further accelerate the transition of the energy system [8]. To promote the transition, the regulatory framework has been changed towards a market system favoring multiple and decentral players besides the large energy-generating and network-operating companies. Nevertheless, the electricity price in Germany is one of the most expensive in Europe, even though the market system has been liberalized by law [9]. In summary, however, it can be stated that Germany is not the leading country in terms of the overall share of renewable energies in total energy consumption by international comparison, but is, at best, average [10].

The energy sector is strongly regulated and of central importance, and it is essential to consider the interactions between the economy, politics, and society and to include these in decision-making processes to be able to act successfully in the long term. As an important basis for the prosperity and functioning of an industrial nation, the sector of electrical energy generation is highly relevant for many stakeholder groups.

This paper summarizes the most important events and decisions of recent decades that have influenced the transition of the German energy system. The focus of our work is on the transition of electricity generation, as this has played the largest role in the entire energy transition in the long term. Nevertheless, the energy sectors cannot be considered completely isolated from each other as they are interconnected, mainly through common sources (e.g., natural gas). The considered factors are grouped into categories and analyzed according to their cause-and-effect relationships. Their interdependence is analyzed in an Ishikawa Diagram (cause-and-effect diagram). In addition, the opportunities and risks as well as the obstacles, including the relevant path dependencies of the energy transition, are considered from different angles. The implementation of some of the possible solutions is being hampered by society and by politics; others are not yet technologically feasible and need further research and development. To sharpen these perspectives, we need to consider them separately at first, to merge them, and to set them into context with each other. This can help to identify what would be the best way to continue with the transition of the energy system, to understand why, for instance, large German energy producers are struggling with their business models, and to determine how to overcome dependencies on critical suppliers, e.g., those located in Russia or the Middle East.

The influences on the energy sector are manifold and can be attributed to society, politics, the economy, the environment, and technology. Their interdependencies are not obvious at first glance. This paper analyzes dependencies and interdependencies and also reflects that not every approach to sustainability or Corporate Social Responsibility (CSR) is measurable or even yields a positive economic output. However, to overcome economic disincentives, politics can provide incentives to induce desired changes. On the other hand, private and corporate consumers can exert great influence on the energy sector by making decisions that modify their consumption patterns and by actively participating in social movements and influencing politics.

To gain an understanding of interactions and interdependencies of the complex process of energy transition and to derive arguments for future developments, we examine the following research question:

Research Question:
How can the events and effects in the course of the German energy transition be classified with a cause-and-effect analysis and which interactions between the events and effects can be identified?

Methods

The transition of the German energy system (Deutsche Energiewende) is one example of disruptive changes that are turning the energy sector into a more sustainable industry. On their path to generating electricity with fewer or even no carbon emissions, the European states have chosen different approaches. In electricity production for instance, France relies on nuclear power in a centralized grid [11]. Denmark already has almost 100% Renewable Energy Systems (RES) in a decentralized grid [12]. Germany can be found between these two extremes. On one hand, the German government is subsidizing decentralized renewable energy production, such as photovoltaics (PV) or wind turbines. On the other hand, the German government also subsidized coal mining in the Ruhr area over a long period, which is mainly used for generating electricity in large coal and lignite power plants with massive CO_2 emissions.

Lately, huge protests against lignite mining and coal-fired power plants have attracted up to 50,000 people to one protest march alone [13, 14]. As a result, the national government has established the so-called Coal Commission (Kohlekommission), which has developed a plan and a timeframe to shut down all coal- and lignite-based power plants. Representatives in the Coal Commission are from different stakeholder groups who should reach a compromise on the future of coal usage in Germany's energy sector [15].

These examples of different European states illustrate how different stakeholder groups and their interactions can lead to different assessments of and solutions for the same problem. In our paper, we show the need to take a holistic view of the process of energy transition due to the numerous actions and dependencies among the stakeholders involved [16].

The three pillars of sustainability and technological improvements

Aim, design and setting of the study

Sustainability is, per definition, an integrated concept, which comprises different perspectives [17]. Most of the literature refers to the three-pillar concept which includes the economic (consumption and investment in productive capital), the social (including human capital improvements through healthcare and education), and the environmental (including the depletion of natural resources through consumption of materials) dimensions [16]. These three pillars are accompanied by political influences, since the supply of energy-relevant resources is playing an increasingly political role, e.g., in political conflicts such as the recent invasion of Ukraine by Russia. The three-pillar concept, including the political dimension, is summarized in Fig. 1.

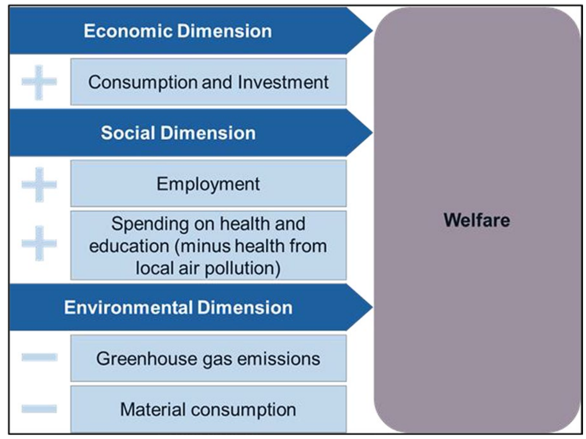

Fig. 1 Dimensions of sustainability (see [16])

This paper creates a detailed understanding of the factors underlying the transition of the German energy system as seen from the different perspectives of sustainability. Based on the three pillars of sustainability, it visualizes the various impacts which have led to the status quo. It also provides an overview of the changing market structures and challenges that electricity generating companies face during current phases and will have to face during future phases of this transition.

Customers, grid management, but also entire sectors are affected by the change towards more sustainable industries. Since the stakeholders of sustainable energy supply are numerous and the energy sector is particularly connected to politics, the necessary ground-breaking changes need to be promoted and deployed without jeopardizing the successful operation of the energy system and major industries. Hence, sustainability and CSR are not only relevant topics for electricity generation and supply but also an important issue for the entire economy [18].

The benefits of the energy transition cannot, therefore, be measured only with traditional indicators, such as cost and revenues. Stern et al. already estimated the cost of not acting in terms of the climate crisis to 5% of the global gross domestic product at least [19]. There will also be tremendous impacts on the environmental and social performance of the reformed energy sector [16]. In the following, we characterize four relevant pillars from the perspective of the main stakeholder or representative. In addition to the three pillars of the sustainability concept, we consider the specific role of technology as a fourth pillar. Technological improvements not only enable the transition of the energy system; they also add to the complexity and enable different paths towards more sustainability. At the same time, technological development creates new path dependencies that will be relevant for the design choice in the years to come. In addition, we consider political developments in the societal pillar that are not the outcome of societal claims for more sustainability but that reflect rather the political conflicts between countries, groups of countries, or regions. In this vein, resource supply is used as a weapon to enforce political interests which are only loosely connected to the energy sector. For this reason, this study adds "Technological improvements" section to the three existing dimensions [20–22]. In consequence, it can be stated that all developments during the energy transition can be investigated in the light of public value.

Economic perspective

The German energy market has been traditionally dominated by few large energy suppliers. Before the liberalization of the energy market these suppliers had defined supply regions without any competitors. After market liberalization, hardly any new competitors were able to establish themselves, partly because the investment requirements were far too high. However, the change in regulations made corporate mergers possible, from which the four large companies that still dominate today—E. ON, EnBW, Vattenfall and RWE—emerged [23].

Precisely these companies have faced considerable challenges due to the deregulation of the electricity market and the changes in the energy mix associated with the transition of the country's energy system. When the energy suppliers were confronted with the economic consequences of these challenges, a large wave of restructuring in the energy market began, which led to—among other aspects—companies being split up, as well as to mergers and acquisitions. Simultaneously, the transition of the energy system has led to the need for new, decentralized solutions, particularly in the areas of smart energy distribution, storage solutions, and grid security [24]. Consequently, new companies were also able to establish themselves in these business areas. These developments have significantly weakened the traditionally oligopolistic structure of the energy market. One example is the so-called energy cooperatives, which, with their local and citizen-oriented character and their focus on the operation of systems for renewable energies, represent a strong antithesis to the large energy companies. Even without the original subsidies and after some regulatory changes, these cooperatives can operate economically successfully and offer a way for civil society to participate in the expansion of renewable energies, in particular, and in the energy market, in general [25].

The Renewable Energy Sources Act (Erneuerbare-Energien-Gesetz, EEG) has had an enormous impact on the development of the electricity market, as PV systems have been specifically promoted and subsidized as private investments. These subsidies have substantially changed the energy mix of electricity generation in Germany and are seen as an important prerequisite of the transition of the country's energy system.

For the four big electricity suppliers mentioned above, this development has had several effects. First, the Merit Order Effect has cut the prices for electricity. This market effect will be explained in chapter 3.1, especially in the section "Economy—3) From the Chernobyl accident to the Fukushima accident in 2011", more in detail. Second, on windy or sunny days, the capacities of conventional fossil fuel-based power plants are no longer needed, whereas these capacities are still required on days when electricity generation from renewable sources is low. These changes in demand have had severe consequences for the economic profitability of Germany's conventional power plants, although Yin and Duan have shown for China, that coal-fired power plants can support the transition towards a renewable energy system in an economically efficient way [26]. Third, the weather-dependent and volatile generation of renewable energy needs to be backed up by conventional power plants to ensure grid stability. In the future, storage solutions can be expected to significantly mitigate this problem. Overall, the changed market structure together with the restructuring of the four largest energy suppliers has formed one of the key premises for the transition of the German sector towards the use of more renewable energy sources.

Environmental consequences

The environmental pillar comprises the impact of human activities on the natural environment as a source (supply of raw materials) and as a sink (absorption of pollutants). These activities are having dramatic effects on the functioning of the earth's ecosystems, which are apparent, for example, in the destruction of entire landscapes, in climate change, and in a dramatic decline of biodiversity. The ongoing climate change in particular has been an important impetus for rethinking traditional forms of energy production and use [27]. Since the corresponding negative environmental impacts materialize as external effects and thus do not (fully) underly market mechanisms, policy-makers have increasingly regulated energy systems in line with many stakeholders and have created economic incentives to reduce negative environmental impacts [28–30].

Society and politics

The social pillar of the sustainability concept addresses the effects of regulatory and economic systems on the living environments of people. This includes aspects, such as fair income distribution, social cushioning of disadvantaged individuals and groups, education, compliance with human rights, equal opportunities, and gender justice. Hence, the energy justice in the transition of the energy system plays an important role, locally and globally [31]. Regarding the energy system, security of supply and a socially acceptable price level are of particular importance [32, 33].

Social systems are influenced in particular by the institutional framework of a society and the voting behavior of the population, but also by political movements, single events—such as Fukushima—and also media coverage. This repeatedly leads to changes in the attitudes of politicians, the population, and decision-makers over time [34]. Some changes in the mindset are at first just represented by a minority and grow over time, some changes are obvious, and some changes are only latent and must, therefore, be stimulated. Political movements, newly founded NGOs, or even new political parties are the consequence of these changes [35]. However, society and politics in Western Europe are usually linked to each other. Big changes within a society affect the decisions made by policy-makers, who operate within a given institutional framework [36]. As an outstanding example, it can be referenced to the protests of the so called "Last Generation" who repeatedly blocked roads and public places, and could achieve negotiations with municipal governments in certain cities [37]. In this paper, the third pillar covers not only society and societal movements, but also political decisions and the political framework in a regulated energy market.

Technological improvements

Since energy transition is also a question of technological feasibility, we introduce a fourth pillar in addition to the three established pillars of sustainability and refer to it as "technological improvements". Hardly any of the past and current changes made to the energy system would have been possible without the corresponding technological changes. These include changes being made in the generation and distribution of electricity, and technological progress taking place in wind energy, photovoltaics, and hydrogen production. Improved information and communication technologies, which allow improved grid management, can also be mentioned here. Specifically, a higher share of decentralized generation of electricity without mechanical inertia creates the need for redundancies and storage as well as a better coordination of the grid. Research and development to improve existing technologies or to create new ones will continue to be a key factor for the success of energy system transformation in the future. For example, smart technologies are increasingly being used for grid control, and more powerful storage technologies are needed to balance the grid. Technological developments, particularly in information and communication technologies, also make it possible to link sectors that were previously operated separately, such as the energy and mobility sectors.

Cause-and-effect analysis

The cause-and-effect analysis is a tool which describes relationships between causes and their effects. Originally, the cause-and-effect diagram was invented and developed by Kaoru Ishikawa as a tool for quality management. Therefore, it is also called the Ishikawa diagram [38].

Characteristics of the method

An Ishikawa diagram usually has the following structure: the core problem to be considered is positioned at the top. Subsequently, the main factors influencing the problem to be investigated are identified and installed as branches along a main axis. The resulting construct resembles the skeleton of a fish, which is why the diagram is also called a "fishbone diagram". In a second step, the main influencing factors are assigned to subcategories which branch off from the large bones as small bones [39]. Thus, an Ishikawa diagram can be used to present the search for and the development of the causes of a problem in a structured and detailed way [38, 40]. Over the course of time, the Ishikawa diagram has also been adopted by other disciplines to explain complex and multi-causal relationships. The use of this method in various research areas shows the versatile possibilities of applying the Ishikawa diagram [40–43].

Description and limitation of the method

Hence, Ishikawa diagrams are also suitable for explaining complex developments, such as those that have led to the transition of the German energy system. Even though the distinction between causes and effects is not always clear, the diagram can show how interdependencies between different factors have affected actions and reactions of multiple stakeholder groups and how these interdependencies have fostered developments in the three different sustainability perspectives as well as technological developments. As all of the four perspectives have contributed to the energy transition in Germany within the last decades, they will be analyzed separately first and then combined in an overall Ishikawa diagram. This approach facilitates not only a better understanding of the transition of the energy system in Germany but also provides the opportunity to draw conclusions on future trends and on developments in other countries.

In this paper we use the terms of "pillars" and "perspective" for the three sustainability pillars and the perspective of technological developments, respectively. These are influenced by different categories which sum up events or influencing factors (see Fig. 2).

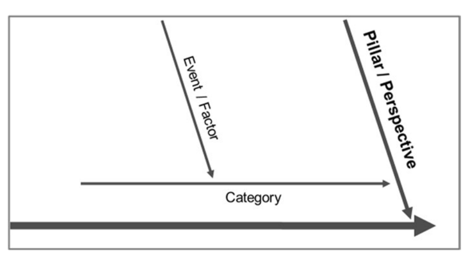

Fig. 2 Nomenclature of the diagram in this paper

Perspectives of the energy transition in Germany

For this study, we searched for all events which concern German politics regarding energy and especially electricity, the transition of the German energy system, and the German regulations regarding electricity generation and distribution from a historical, social, and political point of view. For this purpose, we considered events which have affected at least one of the perspectives and can be seen as starting-point, ending or milestone for development. For each of these perspectives (economy, environment, society, and technological improvements), we identified the factual basis and depicted the identified relationships.

Following the creation of the Federal Republic of Germany in 1949, energy policy was initially seen exclusively as a necessity for the economic development of the country. While concentrated primarily on power generation from hard coal and lignite, the main focus after World War II was on restoring the grid infrastructure and securing the reliability of the electricity supply [44]. After a period of economic and social upswing, and triggered by new ground-breaking scientific findings, German society—alongside emerging political movements—began to question the country's behavior in terms of sustainability. A prominent example is the Club of Rome, which was founded in 1968 [45] and commissioned the pioneering report "The Limits to Growth" from the Massachusetts Institute of Technology in 1972 [46]. This report indicated the problem of population and economic growth that would exhaust the resources of planet Earth within one hundred years. As a consequence, the report stated that economic and policy systems needed to be redesigned towards a higher focus on sustainability. However, this report was only one important factor over the course of time. In the period analyzed in this paper, we consider the timeline from World War II to today and divide this period up into the following distinct phases:

(1) From World War II to 1968 (foundation of the Club of Rome)
(2) From 1968 to the 1986 Chernobyl accident
(3) From the Chernobyl accident to the 2011 Fukushima accident
(4) From the Fukushima accident to 2022
(5) The Russian invasion of Ukraine

Timeline of relevant factors

The cause-and-effect diagram enables the visualization of the type and numbers of categories that are relevant for the different perspectives. Although this approach cannot replace a sound evaluation of every event, the Ishikawa diagram does illustrate relevant relationships in a clear way. Figure 3 summarizes the relevant events and influence factors for the economic perspective.

Economy

For the economy pillar, we distinguish between two types of energy generation (conventional and renewable). Furthermore, we reflect regulatory changes that are relevant for the market structure as well as market developments, such as external shocks and regulatory implications, which have led to changes in revenue and cost structures.

(1) From WWII to 1968, Germany relied on energy generated by coal and lignite, with these resources being mined by large montane corporations, which employed a substantial number of people [47] and required large and cost-intensive assets to be utilized over several decades [48–50]. During the time of Germany's "Wirtschaftswunder" (the Economic Miracle) the economy demanded more and more cheap energy, which ultimately led to high emission levels and severe environmental problems [51–53].

(2) From 1968 to the Chernobyl accident of 1986, a few decades of massive use of fossil energy sources passed. In 1973, the first oil price crisis hit the German energy sector, resulting in higher energy costs for companies and private households. To cushion the dependence on external market shocks and any accompanying economic crisis, politicians increasingly focused on nuclear power [45]. While industry and politics were able to stabilize the energy production, the price levels for energy in Germany decreased [54]. Finally, in the early 1980s, the price levels for energy in Germany decreased [55], with an energy sector in place that was dominated by a few large companies running large fossil or nuclear power plants and supplying electricity via a centralized grid.

(3) From the Chernobyl accident to the Fukushima accident in 2011, the economic conditions underwent radical shifts that were mainly driven by regulatory changes. Since 1990, the share of renewable energy production had been growing continuously. One reason for this was the Electricity Feed Act (Stromeinspeisegesetz), which was introduced in 1990 and fostered by the Renewable Energy Sources Act (Erneuerbare-Energien-Gesetz, (EEG) in 2000 [56, 57], and which guaranteed an economically appropriate feed-in tariff for energy from photovoltaic, wind, and other renewable sources. From the consumer's point of view, 1998 was a turning point, as the electricity market was opened up, weakening the oligopolistic structures. This so-called liberalization of the German electricity market allowed customers to freely choose their supplier of electrical power. With this change in policy, the government targeted high energy prices and market inefficiency. As a consequence,

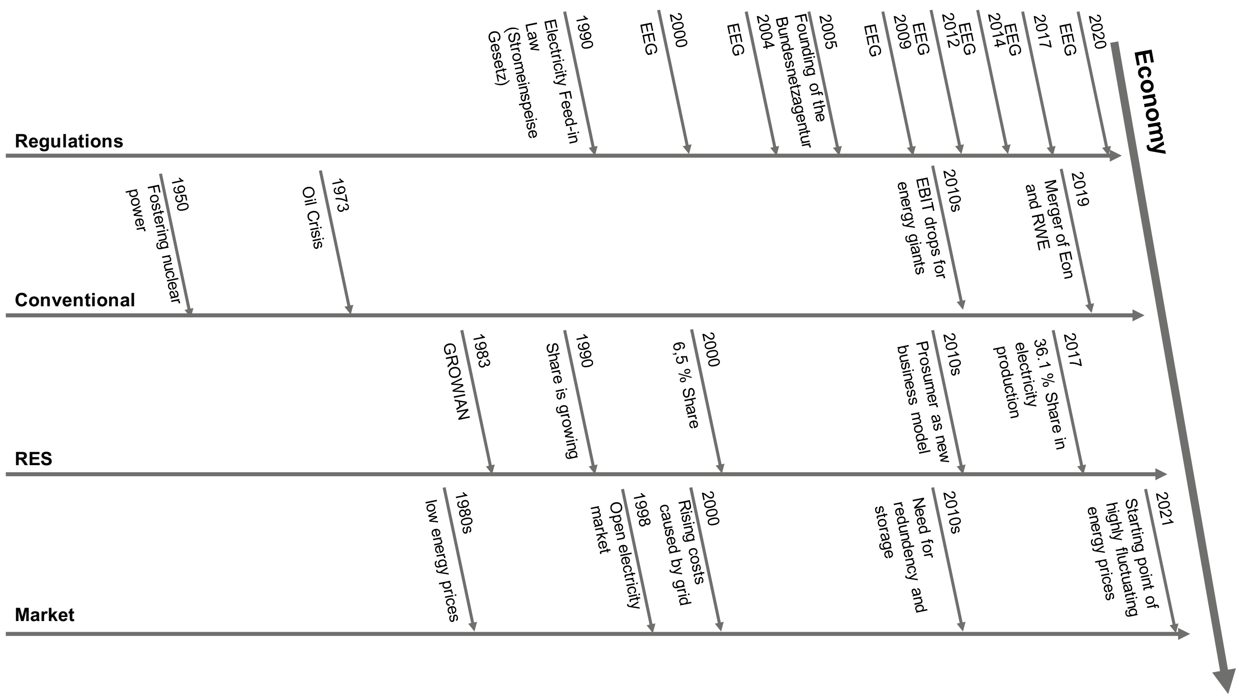

Fig. 3 Economic factors

the energy prices dropped for just a short period before returning to their levels prior to liberalization [58], with the oligopolists being able to maintain their dominant market positions. It should be mentioned that prior liberalization, prices had already been raised considerably to make the effect of liberalization appear more positive. In 2001, only ten electricity suppliers held a market share of 80% in the field of the distributed electricity. During the period following liberalization, the market share of even the biggest electricity supplier in Germany did not change more than 2% over time [59]. However, liberalization did change the price-building mechanisms. The electricity price was now formed at the electricity exchange in a market-oriented manner. For this purpose, each power plant operator submitted a bid for a certain amount of electricity at a certain price. The offered "quantity" of the electricity depended on the installed capacity of the respective power station. The price was based on the marginal costs incurred by the type of power plant concerned. The price of the (marginally) most expensive power capacity consumed was the market price at which the electricity was traded. Thus, most power stations that offered a lower cost-based price were able to sell at a price above cost-based price levels [60]. This effect was mitigated by the first Renewable Energy Sources Act (Erneuerbare-Energien-Gesetz, EEG) from 2000. The EEG not only guaranteed the feed-in of renewable energy, but also a fixed remuneration per kilowatt hour. The gap between the guaranteed feed-in remuneration and the market price was compensated by the EEG-levy [61]. The impact of the EEG act and the resulting pricing structure for electricity and the profitability of conventional power plants were wide-ranging. The available capacities of the renewable energy sources were excluded from the inclusion in the Merit Order. As a result, the demand for traditional production capacities—which was the base for determining the prices—fell, taking into account the provided output of renewable energy generators. Consequently, the intersection of the remaining demand and supply curve shifted towards lower prices, at least when a substantial amount of solar and energy power was fed into the net. This had two consequences. On one hand, the capacities of the expensive peak-load power plants (especially oil and gas power plants) could be used less frequently. On the other hand, the range between price and marginal costs also fell for power plants that were still in use, which led to particularly dramatic economic losses for power generators [60, 62]. As a consequence, the share of renewable energy has not only grown disproportionately since 2004 but also the profitability of the large electricity providers suffered substantially.

(4) From the Fukushima accident to 2022, the German energy transition has gained a tremendous momentum. The market fields have been newly divided and new

regulations, including the obligatory phase-out of all nuclear power plants, have been introduced. The impact has been noticeable along the entire value chain [24]. Especially traditional electricity generators have struggled with the new regulations. Conventional power plants are no longer able to operate economically [63]. The EBITA of E.ON, one of the four largest electricity producers in Germany, decreased by 2.5 billion Euro from 13.3 billion Euro in 2010 to 10.8 billion Euro in 2012 [64]. Similar changes can also be observed in the other three large energy suppliers [24, 65]. Although the principle of "grandfathering", with a discount of 1.25%, was extended to the second EI Emissions Trading System period from 2008 to 2012, this did not help to improve the EBITA of the major energy producers [66]. One reason for that can be seen in the rising share of small-scale units for renewable energy generation, as Fig. 4 [67] shows. The share of renewably generated electricity from wind, biomass, solar sources, and water increased from 23% in 2011 to 34% in 2015 and to 46% in 2019.

Furthermore, the prices on the electricity market have decreased due to subsidies and regulation, but also because the variable (marginal) costs of renewably generated electricity are lower than the variable costs for conventionally generated electricity. Because of the Merit Order principle, the margins of the large fossil-based power plants have now decreased dramatically. Figure 5 shows the average price per year of MWh electricity on the energy stock exchange in Leipzig [68].

In addition, due to the (weather-related) volatility of renewable energy generation units, the price for electricity can be negative at times of high peaks during generation. For large and inflexible power plants, this can be a problem because of their continuous power generation. With a rising share of renewable generation, the volatility of generation has increased and, thus, the trend for hours with negative electricity prices has become more pronounced over time (see Fig. 6). Even if the total share of hours with negative prices is still small, this trend should be noted and may continue in the future with an increasing share of RES. Due to these changes, and as renewably generated electricity has been supported by the EEG and direct subsidies, running a fossil-based power plant has become less profitable, because initial investment costs have become more difficult to amortize.

Even though the energy transition requires high flexibility, which creates problems for large companies with large assets, overall, the German Energiewende has created many economic and non-economic opportunities. Next to objective consequences, such as creating

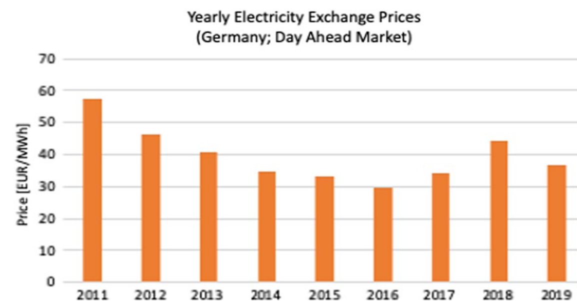

Fig. 5 Average price per MWh on EEX

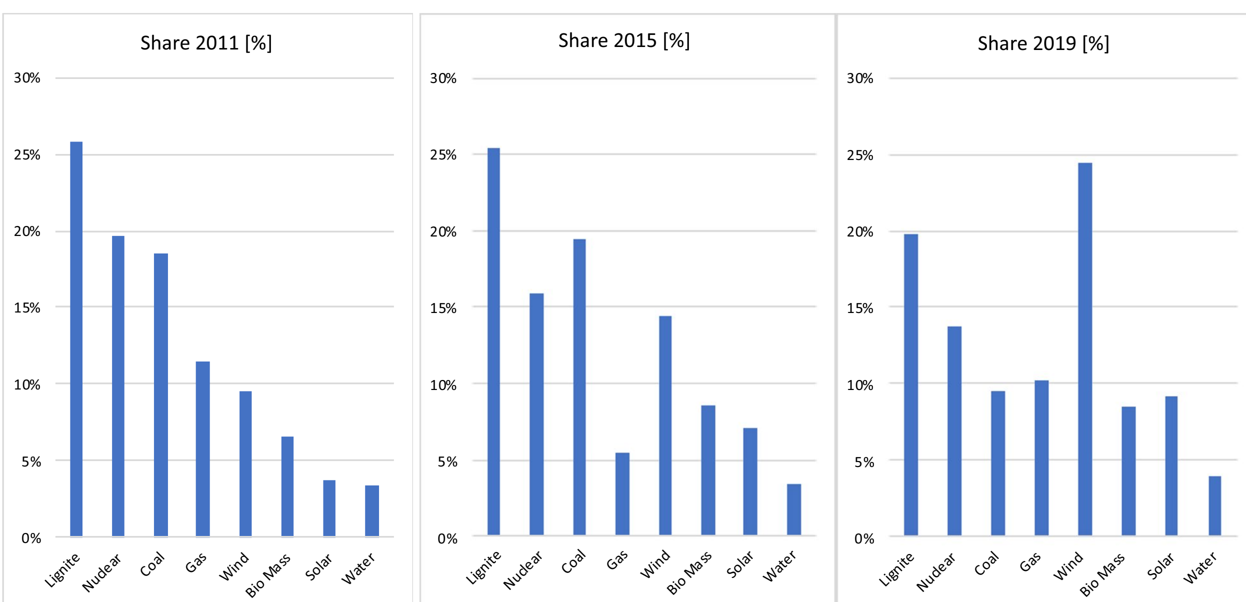

Fig. 4 Share of electricity generation in 2011, 2015, and 2019

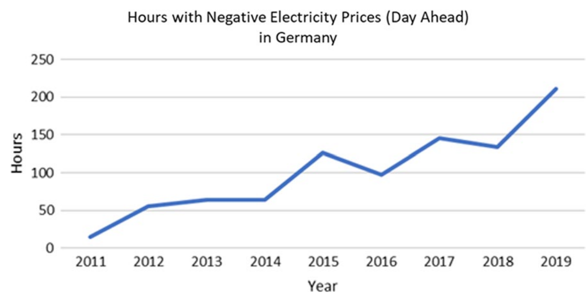

Fig. 6 Hours with negative electricity prices per year in Germany

new industries or business models, there are positive side-effects for wealth [69]. For example, the customer-centric energy supply system enables the creation of additional financial value for the owners of renewable power plants, such as rooftop PV systems. In addition, the avoided costs for environmental damage caused by emissions outweigh the costs for energy transition [19]. In this vein, the energy transition process has also stimulated a transition of the energy supply system which includes the formation of energy communities [25, 70, 71] and the aspiration of many municipalities to take over the local distribution grids [72]. For example, in 2018, two major energy generators and suppliers in Germany decided to merge their companies and to structure their business in a new way. Since competition is not driven between large energy providers anymore but small decentralized energy generators have started to dominate the market, RWE, with its newly founded subsidiary Innogy, and E.ON saw the need to bundle their energy generation sectors and separate them from their grid and supply operations [73]. These organizational restructurings reflect the market shifting from a traditional energy market towards service-based operations, which becomes even more visualized by the highly fluctuating energy prices since the end of 2021. The electricity prices on the day ahead market started to increase and culminated in a mean price of 221.06 EUR per MWh in December 2021 [74]. One reason for this was the increased price for fossil energy carriers.

(5) Russian invasion of Ukraine

The energy price effect was levelled by the war between Russia and Ukraine. At the beginning of the war in February 2022, Germany was importing 52% [75] of its gas consumption from Russia, making it the world's largest consumer of Russian gas in absolute terms. 15% was used to produce electricity [76]. EU-wide, 40% of the gas consumed was purchased from Russia [77]. In addition, Russia supplied 45% of Germany's oil imports [78].

While numerous economic sanctions were imposed against Russia after the beginning of Russia's invasion of Ukraine [79], a full embargo of the import of all fossil resources was not possible due to the high economic dependence on the energy sector. In 2018, then US president Trump had accused Germany of becoming totally dependent on Russian energy supply, but these warnings were not heard [80]. The energy market, which had previously been viewed primarily from an economic perspective, became all the more politicized. Among other things, the "Nord Stream 2" project, which had been pushed forward by Germany for a long time against resistance from the US and other EU states and was almost completed, was canceled [81]. The goal of reducing dependencies on politically less reliable partners came to the fore. The value of independence, or rather the price of dependence, which was almost completely ignored in the procurement of (preferably) the cheapest possible resources, became clear. Alongside the search for new supply options—such as liquid natural gas (LNG)—from overseas, the acceleration of the energy transition towards (regional) renewable energies also moved into the foreground of political discussions. On the electricity market, disadvantages for buyers due to the Merit Order became apparent as a result of the distortions. The increase in gas prices also caused the prices for electricity from gas-fired power plants to rise. As the most expensive source of electricity, electricity from gas increased the overall market price immensely, especially at times of low production from renewable sources.

In summary, the transition of Germany's energy system shifted the economic basis of the established energy sector towards a higher degree of decentralization, a shift which has challenged major electricity providers as well as grid operators. Hence, future electricity generation will be more volatile due to its dependence on renewable resources, such as sun radiation and wind, so there will also be a greater need for redundancy, storage, and smart electricity demand. It can be expected that recent political developments will accelerate the process towards electricity generation from renewable resources (Fig. 7).

Environment

For the environmental pillar, we distinguish between three categories with the most global impact of the energy sector: air pollution due to burned fossil resources which consequently leads to the climate change, nuclear accidents, and environmental catastrophes caused by oil.

(1) From WWII to 1968, the enormous use of coal and lignite caused a sharp increase of several types of emissions. Some areas in Germany, such as the Ruhr area, were extremely affected by exhausts from and the consequences of coal and lignite mining [51–53]. In his speech in connection with his candidacy for chancellor on April

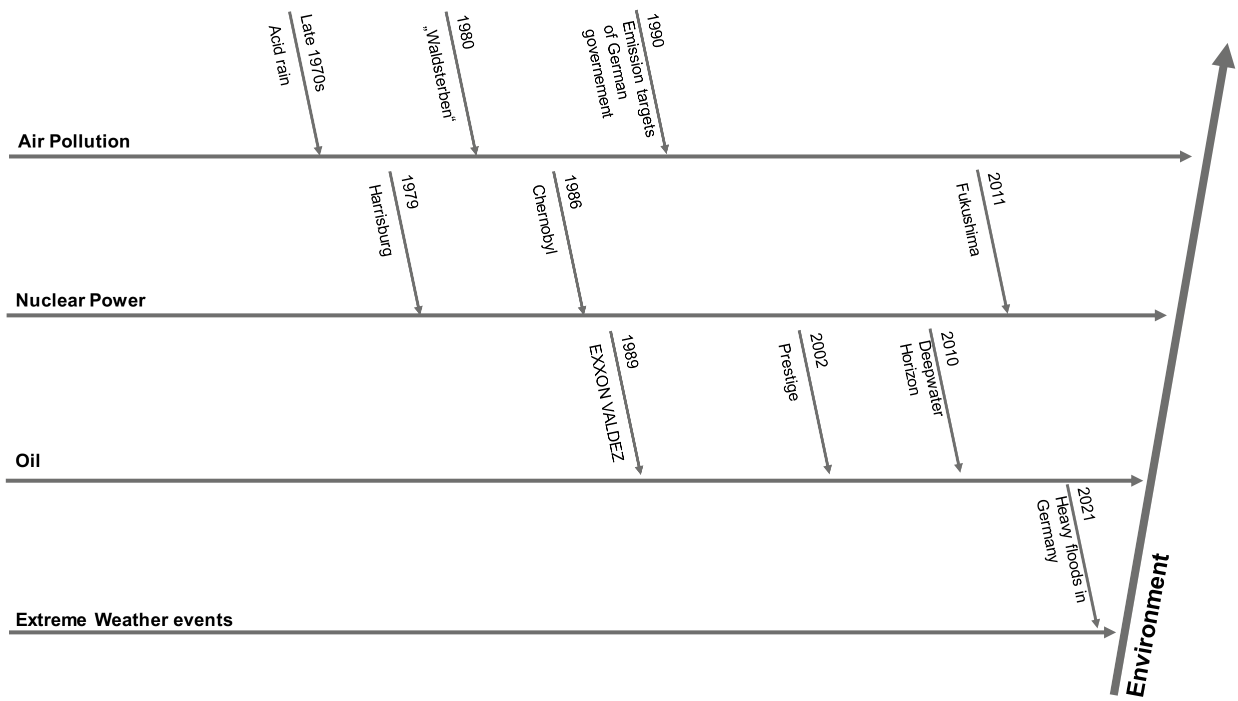

Fig. 7 Environmental factors

28, 1961, Willy Brandt demanded that the sky over the Ruhr area should turn blue again [82]. On one hand, the almost 100 coal-driven power plants were generating cheap electricity and heat, which was helpful for the heavy industry in that region. On the other hand, every ton of pig iron was causing 8.6 kg of dust and the power plants were producing 4 million tons of sulfur dioxide every year [82]. This resulted in higher rates of leukemia and cancer, rickets and blood count changes in the core of the Ruhr area. Newborns in the Ruhr area were on average smaller and lighter than newborns in the Lower Rhine area [82].

(2) From 1968 to the 1986 Chernobyl Accident, nuclear technologies became more popular, but brought even bigger risks with them. The first large nuclear accident was the Three Mile Island accident near Harrisburg, USA, in 1979 [45]. It remains one of the biggest nuclear accidents to date [83, 84]. A closed valve almost led to a nuclear explosion, because the fuel elements were melting and producing hydrogen within the power plant. About 2 m people were affected by the nuclear radiation [85]. In the late 1970s and early 1980s, Europe was facing another problem, which was a result of decades of emitting all kinds of exhaust gases into the environment: acid rain and dying trees (Waldsterben) were challenging German's forests at this time [45]. On January 18, 1985, smog alarm level 3 of 3 was triggered for the first time [86]. Besides air pollution, a nuclear danger emerged with the Chernobyl accident in 1986.

(3) From the Chernobyl accident to the Fukushima accident, national politics in parts of Europe were taking a more critical view of nuclear energy. After nuclear radiation spread over Europe and forests remain partly affected until the present day, no new nuclear power plants were authorized in Germany [87, 88]. Only 3 years after the Chernobyl catastrophe, the Exxon Valdez oil tanker struck a reef off the coast of Alaska, contaminating 2000 km of coastline. Up to 400,000 seabirds and 5000 sea otters died as a consequence [89]. After these dramatic catastrophes with high media coverage, an awareness for the problem of global warming and better protection of the environment arose in German society and other European societies. In addition, the 1990 Electricity Feed Act (Stromeinspeisegesetz) provides for the feed-in of electricity generated from renewable sources to be prioritized [56]. Furthermore, a Europe-wide directive was adopted in 1996 (96/62/EG), which obliged the member states to comply with certain air quality targets.

However, the occurrence of severe and environmentally harmful events did not stop. In 2002, the oil tanker "Prestige" lost 50,000 tons of oil due to a tank leak and 1600 km of the Atlantic coastline in Spain, Portugal, and France were affected. Again several tens of thousands of seabirds died [90]. In 2010, eleven people were killed when the "Deepwater Horizon", an off-shore drilling rig, exploded and 780 million liters of oil contaminated the Gulf of Mexico and the coast of Florida [91]. The latest groundbreaking incident was the nuclear accident at Fukushima in March 2011, caused by the 2011 Tōhoku earthquake and subsequent tsunami. Three units were affected by meltdowns and more than 100,000 people had to leave the area around the power plant, in addition to the dramatic effects caused by the tsunami. Future consequences are still not fully predictable.

(4) From the Fukushima accident until 2022, no major environmental accident has taken place. Nevertheless, discussion about introducing fracking in Germany is ongoing [92]—the consequences of which for the ecosystem are not foreseeable—and energy generation in Germany is still dependent on fossil energy carriers. However, the levels of greenhouse gas emissions and the respective climate change remain a huge concern to the population. Specifically, the flooding events in several areas of Germany in 2021 are often seen as a consequence of worsening climate problems [93].

(5) Russian invasion of Ukraine.

Concrete effects of the war in Ukraine on the environment cannot yet be fully estimated. Nevertheless, known environmental dangers became evident again on an urgent scale. The threat of bombing and/or sabotage of the largest nuclear power plant in Europe posed an environmental threat not only to the parties directly involved in the war [94].

However, political decisions based on this event may have a positive environmental impact in the future. It is currently planned that Germany will terminate its coal and oil imports from Russia by 2023 and its gas imports by summer 2024 [77]. The war could act as an accelerator of the energy transition in Germany, as gaining independence from politically instable suppliers has become a political priority. In this vein, political and environmental interests can complement each other.

Summarizing the overview of environmental catastrophes, these accidents, no matter which category they belong to, appear randomly and cannot be predicted. Their influence on society and politics is analyzed in the following section. In the case of air pollution, which is a more continuous event caused by exhausts, it can be seen that the elimination of the problem often requires years or decades. One reason for this is that technological, economic, and political changes must go hand in hand, as the further cause-and-effect analysis will show. Nonetheless, in recent years, overall emissions in Germany have decreased [95]. However, Fig. 8 also demonstrates that, even if a linear decrease is assumed, the trend of decreasing emissions during the last 30 years is too slow to reach zero emissions over the next 30 years up to 2050 (Fig. 9).

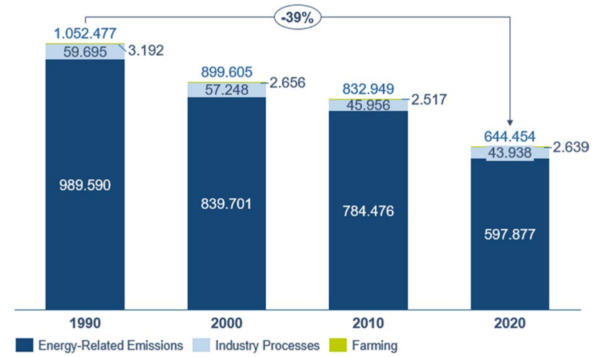

Fig. 8 Emissions of CO_2 Equivalent in Germany from 1990 to 2020 [96]

Society and politics

For the pillars of society and politics, we focus not only on policy measures of the German government but also on supra-national institutions and events resulting in far-reaching contracts and agreements. Since politics follow the consensus of society at least in part, it is important to consider the role of society as well. To do so, we decided to focus on NGOs as organized structures and the green or environmental movement in general—from now on "the environmental movement". Originally, the core agenda of this movement was, above all, the phase-out of nuclear power. In addition, it addressed the pollution in cities, and the movement advocated animal rights [97]. Over time, the environmental movement and its organizations emerged into a complex web of different influences, with many regional and thematic differences among its groups. In addition, a central line of conflict has not always been clear, which makes it even more difficult to define the environmental movement [98]

(1) From WWII to 1968: in West Germany, the Federal Republic was granted sovereignty as an independent state by the Paris Agreements of 1955 [99]. This event created the basis for establishing nuclear power as the second pillar of the German electricity supply alongside coal-based electricity generation. Immediately after the Paris Agreements took effect, the Ministry of Nuclear Affairs was created in 1955 [100], and in 1957 Germany joined the European Atomic Energy Community, EURATOM.

(2) From 1968 to the 1986 Chernobyl accident, the nuclear policy was supported by all the leading parties in Germany. Thus, even the change of government in 1969, with the first takeover of power by the Social Democrats (SPD), did not change the political position on power generation from nuclear energy [101]. At the same time, the Club of Rome was founded as a federation of scientists, who called attention to the limits of growth and natural resources as well as environmental risks. Backed

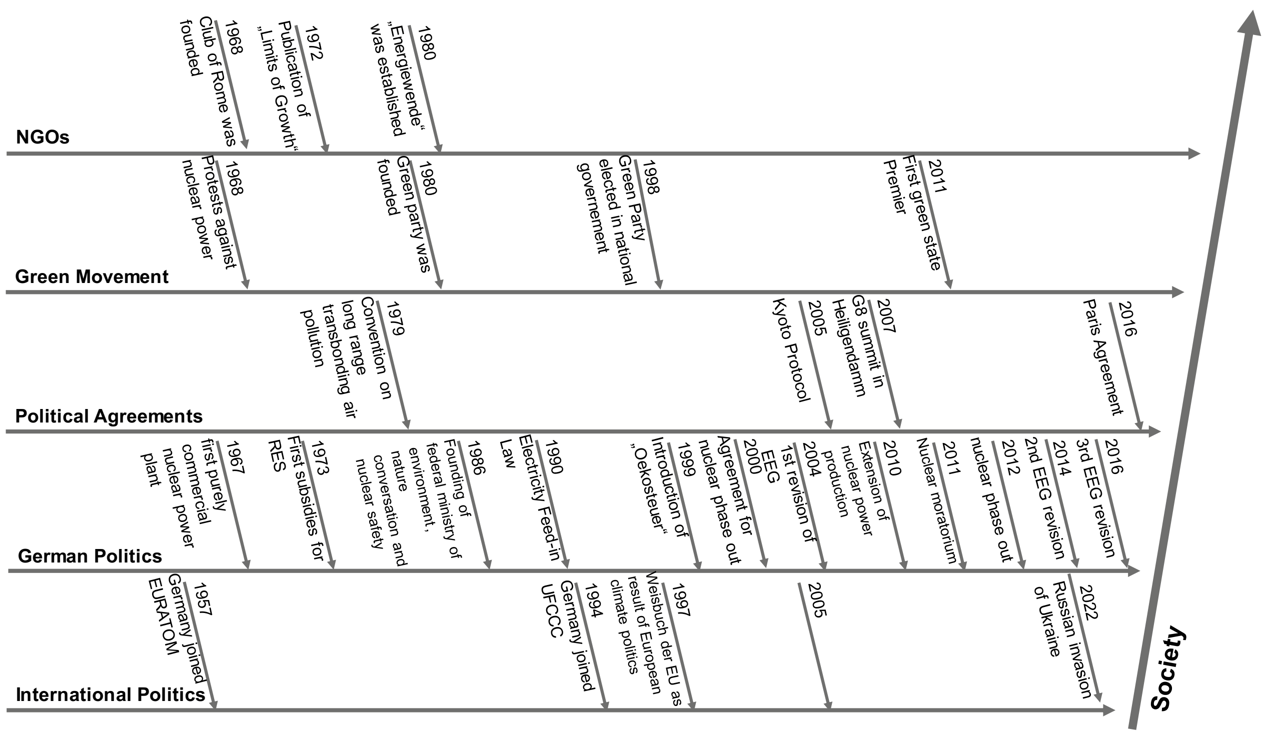

Fig. 9 Societal and political factors

by scientific concerns and other influences, anti-nuclear protests started in Germany and the 1968 student protest movement (68er-Bewegung) changed the country's society fundamentally [45]. The oil crisis in 1973 also contributed to a rethinking of the German energy policy for the first time. The aim was to increase independence from fossil fuels, especially those that had to be purchased from abroad. These developments triggered measures in two directions. On one hand, the importance of nuclear power generation was emphasized once again, as this increased the country's independence from fossil resources. On the other hand, however, the first political effort was made to promote renewable energy sources. Around 10 million DM [5.1 million €] were made available to promote renewables in the 1970s, at this time almost exclusively photovoltaics. Even though this amount was fairly small, it was the first political subsidy for renewable energies in Germany [44]. This public funding was continued in the following years. In 1977, a 25% subsidy for investment in solar systems and heat pumps was introduced. However, as this subsidy was not sufficient to make such investments economically feasible, it was not broadly adopted, and remained almost without consequences [102].

In the years that followed, German society became increasingly critical of the increasing and high levels of emissions and water pollution. As a consequence of growing public pressure, environmental protection became an important topic on the political agenda. Thus, the "Convention on Long-Range Transboundary Air Pollution" was signed in 1979 to reduce air pollution as a reaction to the already mentioned Waldsterben of Germany's forests [103]. In 1980 the term "Energie-Wende" (nowadays: Energiewende, which means "transition of the energy system") was used for the first time in a publication by the Öko-Institut [104], which called for changes to energy politics in Germany as well as in all industrialized countries. It suggested a new way of supplying energy, which would be politically and socially advantageous, by decoupling economic growth and energy demand from primary energy sources. The term was given a further boost by a book from the Öko-Institut: "Die Energiewende ist möglich" ("The energy transition is possible") [105]. The English term „Soft Energy Paths" was coined by Amory Lovins as early as 1976 and was also the title of his publication "Soft Energy Paths: Towards a Durable Peace" published in 1978 [106].

Energy efficiency played an essential role in the discussion to reduce energy demand in the long run. In the following years, the term "Energiewende" continued to be used and described the phase-out of fossil resources as the basis of the energy system. As mentioned, new scientific findings published by the Club of Rome and the Öko-Institut further raised public awareness for environmental topics and ultimately led to the founding and establishment of the Green party that emerged from the movement against nuclear power [107]. Even though the Green party did not enter the government until 1998, its influence was already obvious. In 1983, the "Greens" exceeded the 5% threshold and entered the Bundestag, the German parliament [108]. This was the first time that a party was represented in the German Bundestag which clearly opposed nuclear power and advocated the expansion of renewable energies [109]. The Chernobyl disaster in 1986 further accelerated the political change process and the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit und Verbraucherschutz) was established in 1986 [110].

(3) From the Chernobyl accident to the Fukushima Accident the change in the mindset of German society and politics continued. In 1990, the law for the promotion of renewable energies (Stromeinspeisegesetz) was passed. For the first time, electrical system operators were obliged to feed-in the electricity generated from renewable sources into the grid. In addition, the companies were obliged to pay fixed rates for the "renewable" electricity fed into the grid [56]. For example, electricity from hydropower, landfill gas, and sewage gas as well as from biological residues and waste materials from agriculture and forestry was to be remunerated at a rate of at least 75% and electricity produced with PV systems or wind turbines at a rate of at least 90% of the average revenue per kilowatt hour.

In 1992, 20 years after the first united nations conference on human environment, the second united nations conference was held under the headline of environment and development in Rio de Janeiro. The focus of this conference was on the interdependences of the factors of environment, society and economy and how they interact to each other [111]. In 1997, the "White Paper for a Community Strategy and Action Plan" of the EU was ratified. To mitigate climate change, the central point was to set the minimum share of renewable energy sources in gross domestic energy consumption at an average of 12% in 2010 for the entire EU. This document was the cornerstone of the pan-European climate policy, as it established the idea of burden-sharing within the EU and also referred to the outstanding results of the climate conference in Kyoto at that time, on the basis of which more precise targets were agreed [112]. The Kyoto conference in the same year is still seen as the most groundbreaking world climate conference to date. After long negotiations, various targets for the reduction of CO_2 emissions were adopted there. For the 15 member states of the EU at that time, a total reduction in emissions of 8% was set for the period 2008–2012 compared to the base year 1990 [113]. The idea of burden-sharing was implemented in the Kyoto Protocol as well and formed the basis of the EU Emissions trading scheme (EU ETS), first introduced in 2005 [114].

In the coming years, several additional measures to transform the energy system were implemented. With the entry of the Green party into the government in 1998, the phase-out of nuclear energy was brought forward [115]. In agreement with the operators, a decision was made to phase out nuclear power plants (NPPs) without compensation payments and the remaining time of already operating NPPs was limited to 32 years. In the year 2000, the Renewable Energy Sources Act (Erneuerbare Energien Gesetz; EEG) was passed with the votes of the Social Democratic party (SPD) and the Green party. The aim of this law was to initiate a sustainable energy supply. The share of renewable energies in electricity generation should be at least doubled by 2010 in accordance with the above-mentioned targets of the European Union and the Federal Republic of Germany itself. The core of the law comprised fixed feed-in tariffs for electricity from renewable sources [57]. Grid operators had to feed-in electricity from renewable resource and to pay fixed prices per kWh independently of when and how much energy was generated. Wind was initially enumerated with 9.10 ct/kWh in the first 5 years and then decreased step by step to 6.19 ct/kWh. PV was initially enumerated with 50.60 ct/kWh [57]. The additional costs from the EEG were paid by all consumers. The corresponding EEG levy was introduced for this purpose, which must be paid by all consumers in proportion to their electricity consumption. Specific industries could be exempted depending on their dependence on electricity. In addition to that, the government introduced the so called eco-tax (Ökosteuer), which again increased the prices for the customers by another 2.05 ct/kWh [61]. However, the EEG has not only led to rising electricity prices, but has also ultimately laid the foundations for the economic viability of electricity from renewable energies. With the feed-in tariffs being in general much higher than the cost per kWh generated with fossil fuels or nuclear power, the EEG has, therefore, contributed significantly to the economic changes in the energy market discussed above. The EEG thus formed and continues to form a milestone for the transition of the German energy system.

In 2002, the coalition government pushed ahead with the phase-out of nuclear power generation. Shortly before the end of its first legislative period, the coalition of the Social Democrats (SPD) and the Green party passed the Act for the Orderly Termination of the Use of Nuclear Energy for the Commercial Generation of Electricity (Gesetz zur geordneteten Beendigung der Kernenergienutzung zur gewerblichen Erzeugung von

Elektrizität) [116]. As a result, two key decisions were taken: there was a ban on the construction of new nuclear power plants, and it was decided the regulations would lead to the last nuclear power plant going off the grid in 2021 [116]. Development in the area of renewable energy sources was to be continued as well. The first amendment to the EEG was adopted in 2004. This affected the feed-in tariffs for wind turbines. The period for the initial remunerations of onshore wind turbines was increased to 5 years before a basic remuneration was guaranteed. For offshore wind turbines, the period for the initial remuneration was at least 12 years. In addition, the law was adapted to European framework conditions [117].

The federal elections in 2005 resulted in a coalition of the three major parties CDU/CSU and SPD but did not put a hold on the transition of the energy system. The new coalition agreed on further promotions of renewable energies. Contrary to previous statements, the CDU/CSU no longer opposed the EEG. The government agreed on clear targets for the development of renewable energies [118]. However, the disagreement about the future development of nuclear energy remained unchanged. While the Social Democrats (SPD) sought to further accelerate the nuclear phase-out, the Conservative CDU/CSU argued in favor of maintaining the existing plans.

On the international level, the G8 forum decided to reduce carbon emissions by 50% by 2050 [119]. In addition to these fundamental changes, international politics focused on further factors with considerable impact. In 2005, the EU Emissions Trading System, EU ETS, was introduced, allowing burden-sharing between member states according to the Kyoto Protocol. The EU ETS also put a cap on industry-based carbon emissions. Within the cap, companies receive or buy emission allowances for greenhouse gas emissions. Several platforms, such as the EEX Leipzig, permitted direct trading of these allowances. As the energy sector emits most of the CO_2 emissions in Germany and in the EU [120], companies belonging to the energy sector were most concerned by the EU ETS [61]. In 2007, the G8 summit in Heiligendamm (Germany) was held and was accompanied by strong protests from environmental activists. After widespread debates, the summit ended with a common declaration for international climate protection [45].

In 2005, when the EU ETS was introduced, Germany created the Federal Network Agency (FNA; Bundesnetzagentur) in the same year. The aim of the FNA, a regulatory office for electricity, gas, and communication markets, is to foster the competition in the energy market by guaranteeing non-discriminatory grid access [121]. Respective measures have been accompanied by grid access for the many decentralized electricity suppliers, e.g., operators of PV panels, which are thus treated equally as large power plant operators in terms of grid access [122].

Meanwhile, the political decisions became more critical towards a faster transition of the energy system in Germany. In this vein, the federal government extended the lifetime of existing NPPs by an average of 12 years to use nuclear power as a bridge technology for the energy transition [123]. Moreover, 90% of the income of 17.5 billion € of the Ökosteuer (eco-tax) was used to finance the pension insurance budget and only a small amount of the tax was used to support renewable energy [61]. Besides that, some argued that the mechanisms of supporting renewables and the subsidies for renewable energy generation imposed “high costs without any positive impacts on emission reductions, employment, energy security, or technological innovation” [122]. While Germany was already well-known for its leading role in the transition of its energy system, (see [124]), some of the regulations implanted during this period did not further promote the underlying processes [122]. However, the political and societal mindsets changed dramatically with the 2011 accident in Fukushima.

(4) From the Fukushima accident to 2022, society and politics have focused on the phase-out of NPPs and of fossil power plants. Following the accident on March 11, chancellor Merkel announced a nuclear moratorium only 4 days later on March 15. This moratorium obliged NPP operators to shut down the seven oldest reactors immediately with the reference to a security paragraph of the Atomic Energy Act (Atomgesetz) [45, 125]. A remarkable outcome for German society was the election result for the state government of Baden-Württemberg on March 27, 2011. For the first time in Germany’s history, one of its federal states elected a minister president from the Green party, even though Baden-Württemberg had been known as a conservative state dominated by the Christian Democrats (CDU) for more than five decades [126].

While energy prices increased substantially over time due to the higher share of electricity from renewable energy sources, society has held on to this development [127]. During the period from 2002 to 2020, the share of electricity from renewable energies (water, bio mass, wind, and solar) in Germany rose from 8.65% to 53.14% [128]. This sharp increase was a result of an agreement between the federal government and major power utilities for the nuclear phase-out without compensation payments [45], and the subsequent law for phasing out all NPPs by the year 2021 [129]. After the Fukushima accident, the EEG was repeatedly revised (2012, 2014, and 2016). The central challenge of the adjustments made was the sharp rise in prices for end-consumers as a result of the EEG levy and the simultaneous insufficient increase in the number of production facilities. Especially the share of PV increased since 2010, as can be seen in Fig. 10 [128]. However, as PV plants can be seen as private investments with fixed and subsidized revenue, the EEG has had a crucial role in the German energy transition. Despite all criticism, German society still supports this policy. In a survey, 88% of the respondents expressed their support for the transition process [127]. Many promotors even endorse a faster transition to mitigate climate change. For instance, in 2018 protests against lignite power plants mobilized more than 36,000 people in Germany [130]. These protests led to the creation of the so-called “Coal Commission” (Commission on Growth, Structural Change and Employment), which developed a recommendation for political decision makers on how to phase-out coal- and lignite-driven power plants in Germany by 2038 [131]. This recommendation was agreed on by the German Bundestag in 2019 and resulted in the Coal Phase-out Act (Kohleausstiegsgesetz).

In the 2021 federal election, the Green party was able to improve its total vote by more than 50% and to achieve renewed government participation [132]. As a result, responsibility for climate protection, among other things, was transferred to the Green-led Ministry of Economics [133].

(5) Russian invasion of Ukraine.

The Russian war against Ukraine is an example of an event that accelerates ongoing changes in the energy system, but it also shows the complexity of decision-making due to different interests and necessities in energy policy. As already described in the sections *Environment* and *Economy*, Germany made itself dependent on Russian oil, especially gas supplies and now the price had to be paid also at the political level. Even though there was a political will to economically isolate Russia at the beginning of the war, which was implemented in many sectors, trade in fossil fuels was not immediately suspended out of concern for economic damage to Germany. The fact that the Minister for Economy and Climate Change Mitigation from the Green party went to Qatar—a country criticized for human rights violations—to negotiate supplies of LNG, shows the tension in which energy policy decisions sometimes have to be made [134]. The picture is complemented by the Liberal Finance Minister, Christian Lindner, who introduced state subsidies to reduce petrol prices, which had risen after the start of the war [135].

Overall, the political decisions which led to the ongoing transition of the German energy system were influenced both by complex interactions of various stakeholder groups and by singular events. In addition, the environmental movement established a strong political force in the Green party, which has linked scientific findings on climate change and other environmental impacts with its political positions.

Technological improvements

The perspective of technological improvements describes developments in the fields of wind and PV technologies, and a general category, which reflects the progress in other areas, such as electrical grids, hydrogen production, nuclear power or emerging smart technologies. Along with the policy measures discussed above, these technological improvements led to substantial efficiency gains in favour of an increasing share of electricity from renewable energy sources, and resulting in a shift of the

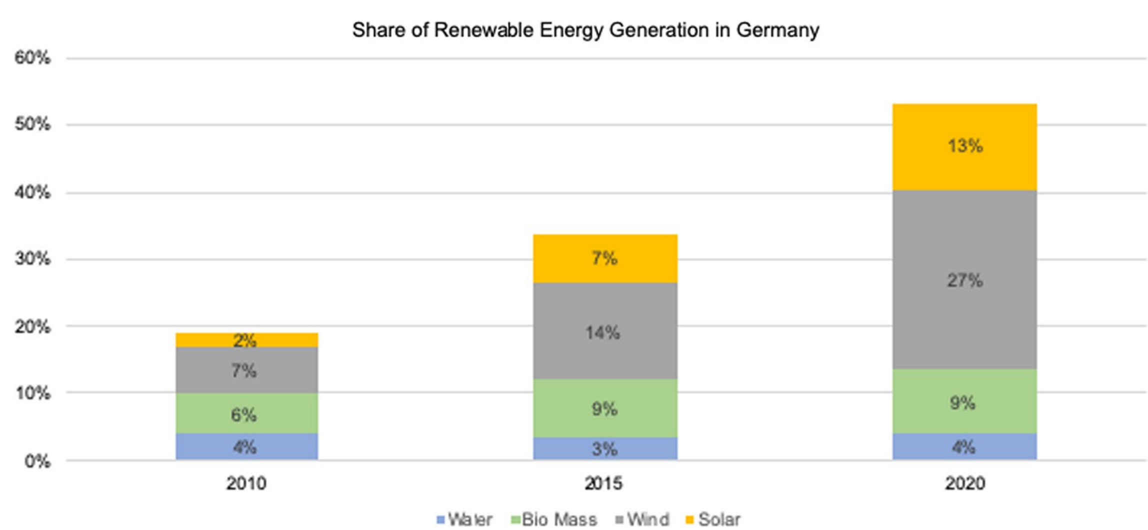

Fig. 10 Share of renewable energy generation in Germany

underlying costs discussed when focussing on the economic pillar (Fig. 11).

(1) From WWII to 1968, the economy was growing fast in West Germany and more energy was needed, which required new power plants as well as new power lines. After the world's first nuclear power plant (NPP) to supply an electricity grid was commissioned in the Soviet city of Obninsk in 1954 [136], and the world's first full-scale power plant with nuclear power opened in Calder Hall in England in 1956 [137], Germany also focused on building its first NPP. In addition to existing power generation methods, Germany started to use nuclear power in the 1950s and built the country's first nuclear research reactor in 1957 [45, 138]. To successfully advance nuclear energy and to become less dependent on the economically weakening domestic coal industry, several nuclear programs were set up in the years 1955, 1963, 1967, and—as a consequence of the oil crisis—in 1973 [139]. These programs financed research and development activities as well as extensive training courses for nuclear physicists, radiation experts and engineers for the operation of nuclear power plants. Due to a lack of experience and to the tremendous brain drain prior and during World War II, a completely new workforce of engineers and technicians with professional knowledge in this area had to be built up. All these efforts were successfully pursued, and in 1967 the first purely commercial NPPs in Germany began their operations in Würgassen and Stade. In the same year, the first German nuclear waste storage facility was opened at the Asse mine in the federal state of Lower Saxony.

(2) From 1968 to the 1986 Chernobyl accident: after the opening of the first NPPs, the activities of German nuclear research shifted towards waste management and unrelated new technologies, such as microelectronics, computer technologies, and environmental science [138]. In parallel, the first oil crisis along with increasing fuel prices and mounting supply risks improved the economic advantages of nuclear power and made Germany more independent from the importing of fossil resources [140].

At the same time, other countries started to increasingly focus on energy from renewable sources. In Denmark, for instance, the use of renewable energy was already supported at this time. Danish companies started to produce wind turbines in series in the late 1970s [45], leading to technological improvements in on- and offshore wind turbines. German energy companies tried to profit from these improvements and invested in first pilot projects [45]. For example, the Growian project was launched in 1983. A wind turbine with a rotor diameter of 100 m and 3 MW power was planned as a demonstration project for large-scale wind energy transition. However, due to technical problems, the project was closed only 2 years later in 1985 [141].

Rapid material fatigue on the blades, hub and rotor brake, among other things, which could be attributed to the design of the plant, meant that the plant was ultimately only in operation on 17 days [142, 143]. In this

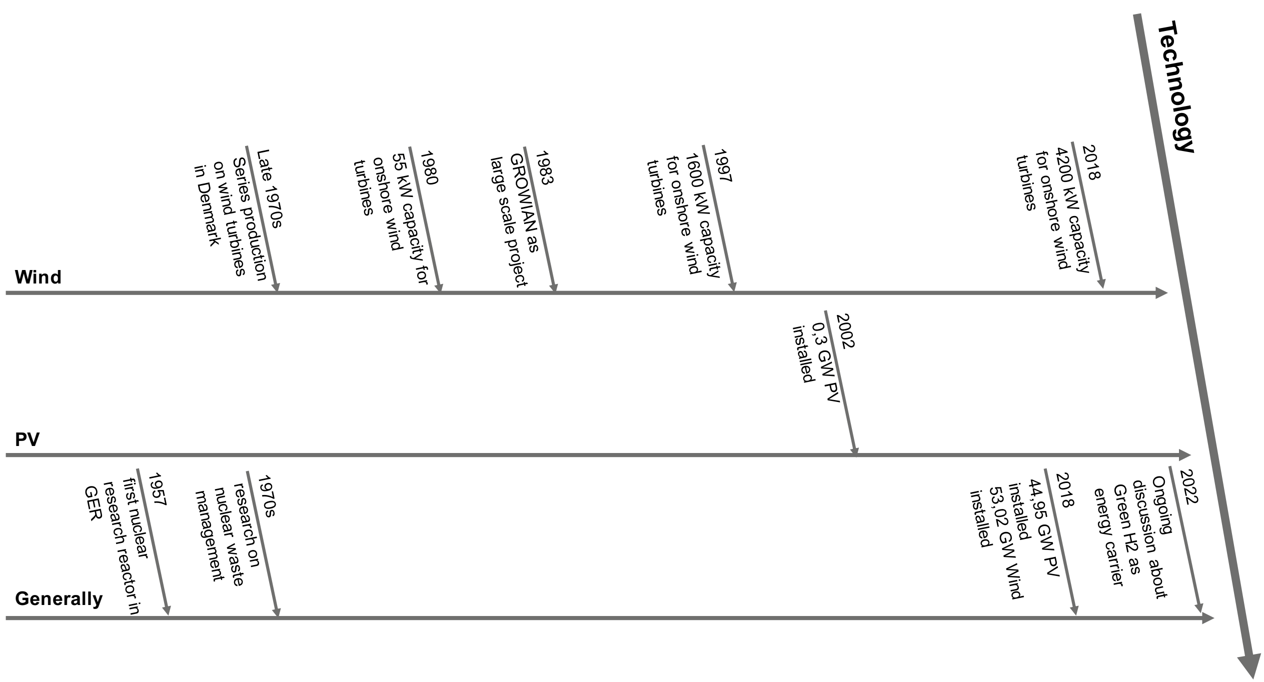

Fig. 11 Technological improvements

case, however, the operators, a consortium of electricity companies, were not unhappy with this either, as this project offered good reasons for the continuation of nuclear power for the time being [144].

(3) From the Chernobyl accident to the Fukushima accident, the nominal power of a single wind turbine increased from 150 kW in 1986 to 6000 kW in 2007 and the rotor diameter rose from 25 m in 1986 to 127 m in 2007 [145]. Furthermore, the costs for rooftop PV systems of up to 10 kW_p halved in the years from 2007 to 2011 [146].

(4) From the Fukushima accident to 2022, and already some years prior to Fukushima, research in alternative energy production has intensified. In 2009, the German government agreed on subsidies to compensate for the lack of competitiveness of new technologies. The EEG regulated the remuneration of electrical energy produced by renewable sources, including biogas, wind, and PV. Even though PV was the most expensive technology to generate electricity from renewable sources, it was the financially most supported one [122]. Hence, the installed PV capacity rose from 0.3 GW in 2002 to 51.99 GW in 2020. However, onshore wind energy generation also increased from 11.98 GW in 2002 to 54.14 GW in 2020 [147]. Technological progress has contributed, among other things, to the fact that the gross generation of electrical energy in on- and off-shore wind turbines increased to more than 100 TWh per year in 2017 [148]. The current maximum capacity of a single on-shore wind turbine is up to 4200 kW with a rotor diameter of 127 m [149].

Furthermore, there are ongoing discussions about green hydrogen as an energy carrier, since there is already an established infrastructure, and hydrogen could be used as storage for electricity in peak times. With increasing costs for fossil fuels, the production of green hydrogen is becoming even financially an alternative [150]. However, it should be noted that Germany will not be able to produce the required amount of hydrogen from renewable energies itself today or in the future. For this reason, Germany is already seeking cooperation with Australia and countries in South and West Africa. In these countries, the conditions are particularly suitable for producing wind and solar power for the production of hydrogen [151].

(5) The Russian invasion of Ukraine.

The war in Ukraine has not led to any concrete technological improvements so far. Thus, the integration of the electricity grid into the ENTSO-E has already taken place and has been brought forward by 1 year [152]. However, the abandonment of the Nord Stream 2 project demonstrates the political willingness to change the financing and funding of individual technologies, too. If the German operating company is banned from commissioning or denied certification, it could face claims for damages amounting to €10 billion [153]. Hence, the political and economic necessity of an increased energy autarchy might probably increase the promotion of technologies related to renewable energy production (Fig. 12).

In summary, technological improvements, on one hand, have enabled the energy transition; on the other hand, technological progress also poses a limitation to even faster and more comprehensive changes. The development of renewable technologies that can quantitatively and qualitatively cover the needs of both society and the economy has been a lengthy process, as the infrastructure, such as electricity grids, has had to be adjusted as well. Nevertheless, huge improvements of several technologies that rely on renewable energies have substantially contributed to the ongoing transition of the German energy system. It can be expected that the Russian invasion of Ukraine will further accelerate this process (Fig. 13).

Causes and effects

After describing the relevant influencing factors for the German Energy Transition, the following section indicates the interactions between the individual factors. Not all cause–effect relationships can be objectively demonstrated, but it is essential to understand the Energy Transition in its entire complexity to visualize the most important interactions. We will now examine the four perspectives together while retaining the temporal structure of the previous chapters.

(1) From WWII to 1968: at the time of Germany's economic development, there was one maxim for the provision of electrical energy: as the backbone for the development of Germany's economy, the energy supply needed to be inexpensive and efficient. Accordingly, government and political parties backed and supported this focus towards economic growth: early on, active nuclear policy was pursued by establishing the Atomministerium

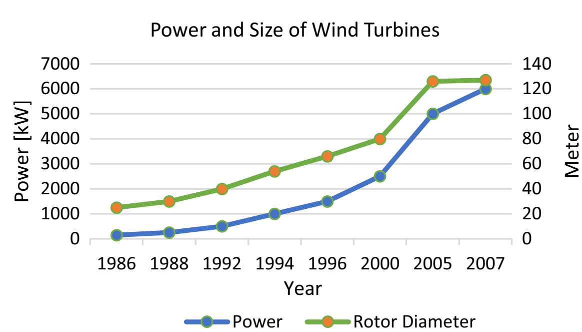

Fig. 12 Power and size of wind turbines

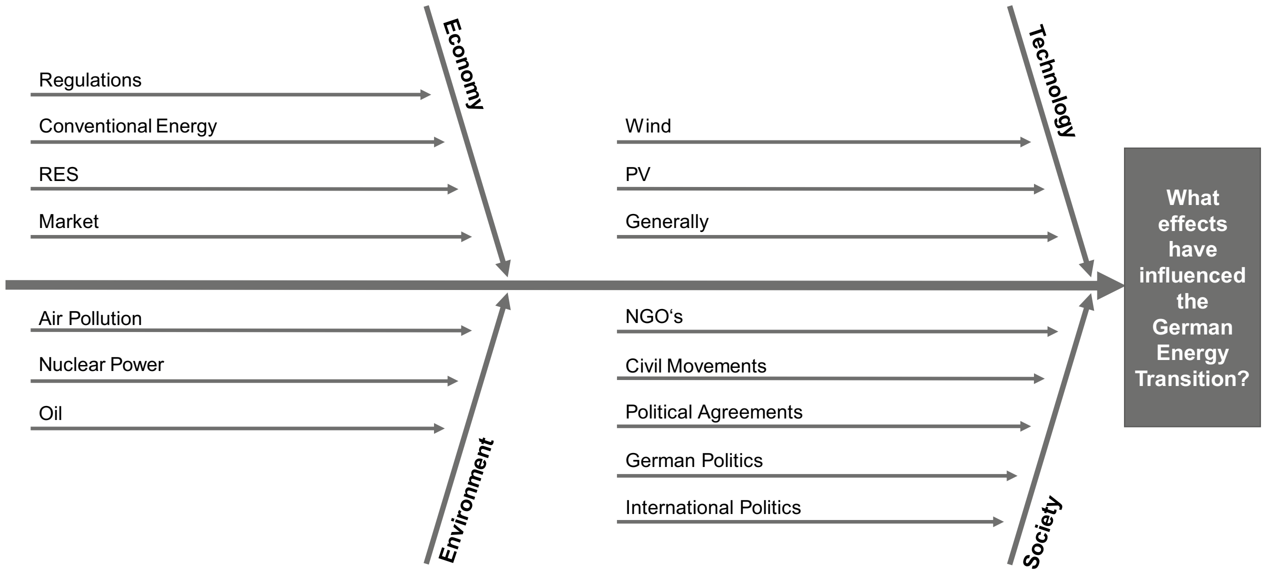

Fig. 13 Ishikawa diagram, causes and effects of the German energy transition

(Ministry of Atomic Energy), which promoted and enabled the development of commercial nuclear power generation.

(2) From 1968 to the 1986 Chernobyl accident: initially, the electricity supply in Germany was based mainly on fossil fuels. At the same time, the first negative effects of this policy became visible: the population in some regions, especially in the heavily polluted Ruhr area, was suffering from various medical problems. This also had an impact on politics: air pollution was an issue in the 1974 election campaign but did not lead to a general negative attitude towards the status quo of existing and installed energy technologies.

The oil crisis can be seen as the first external trigger. The German public became aware of the great dependence on fossil (and imported) energy sources, and this strengthened the will of all parties to promote nuclear power generation. This enabled the electricity producers to develop a second mainstay while securing great potential for significant earnings. The outcome was a system of fossil and nuclear energy sources with low electricity prices and good earning opportunities for the energy utility companies, supported by politics.

This system raised awareness of mounting environmental problems: the first nuclear accident occurred in Harrisburg, USA, in 1979 and—concerning Germany—noticeable environmental damage, such as acid rain and forest dieback. This resulted in growing environmental concerns among parts of the population. The so-called "Green Movement" was formed, culminating in the foundation and later entry into the German parliament of the Green party. First steps in renewable energy production were made. For example, the development of new wind turbines made great technological progress in the 1980s but—without any political support at that time—no success could be achieved.

(3) From the Chernobyl accident to the Fukushima accident: another external trigger was the Chernobyl disaster. The radioactive accident dramatically highlighted the dangers of nuclear power generation and created a general political awareness of the need for environmental protection measures. The Green Party in Germany was no longer isolated with their positions in parliament. As a consequence, the Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety) was established. In this case, it was an external event which triggered changes in political objectives that had already taken place among parts of the population at an earlier stage.

In 1990, the first step towards the active political promotion of renewable energies beyond the funding of research and pilot projects was the Electricity Feed Act (Stromeinspeisegesetz), although this law had few consequences at the onset. However, awareness of the need to reduce the emission of greenhouse gases was growing internationally, too. With the Kyoto Protocol and the first EU-wide regulations for emission reduction, Germany agreed to intensify its efforts to reduce greenhouse gas emissions.

With the entry of the Green party into the German Federal Government in 1998, nuclear skeptics and representatives of the environmental movement, which had been running for almost 20 years, came to power for the first time. This also had immediate consequences. In 2002, the Atomgesetz (Atomic Energy Act) was passed, which stipulated that all nuclear power plants should be shut down by 2021. This act provided planning security for the energy companies as to when their profitable "cash cows" would be shut down.

At the same time, the first version of the EEG (Renewable Energy Sources Act) was introduced. With the feed-in tariff and the exception of the Merit Order, the share of renewable energies rose rapidly. Now, the market liberalization that had been implemented years earlier was having consequences. The profitability of the energy companies' base–load and peak–load power plants declined. The will of broader parts of German society was translated into political measures with immediate economic impact as soon as the promoters of renewable energy generation gained a political majority. New subsidies (1st amendment to the EEG in 2004) also led to rapid increases in the output of wind and solar power. It became clear that—with the appropriate political measures—the success of green technologies could be secured, including their further technological development.

In 2005, the Green party had to leave the government and there was disagreement between the conservative Christian Democrats (CDU) within the coalition and the Social Democrats (SPD) regarding the nuclear phase-out. After the following elections, the Christian Democrats and the Liberals (FDP) formed a government. In 2010, using their majority in the Bundestag they extended the remaining operating life of German nuclear power plants again [154]. This change in the political course created a certain amount of economic uncertainty for energy providers and technology companies.

(4) From the Fukushima accident to 2022: the extension of the lifetime of nuclear power plants deviated from the long-term political line and somewhat contradicted the social opinion, which became apparent in the wake of the Fukushima disaster in 2011. Within a few days, the German government agreed on a shutdown of the oldest nuclear power plants as an immediate consequence. The population also reacted strongly to this event: surprisingly, the first Green minister–president of a German federal state was elected shortly afterwards in a traditionally conservative region in Germany. The remaining lifespan of nuclear power plants was shortened again. Once more, an external trigger had intervened and changed the political course with direct economic consequences.

In the further course of events, the volume of renewable energy production increased in line with the political will of major parts of the German population, supported by further amendments to the EEG. This led to a further decline in market prices for electricity, and periods with negative market prices for electricity were rising significantly in duration and frequency. This also weakened the economic role of the fossil fuel-based power plants that still played an important role for the established large energy companies.

The reaction to this development from the energy companies came late: in 2018, a necessary restructuring of the major energy companies, such as E.ON and RWE, took place, separating the new business areas from the expiring fossil-based business models. In the end, political conditions had initiated a change within the largely regulated energy market, which created new players and shifted circumstances, to which the established players had to react after a prolonged hesitation. This development culminated in the decision to phase out coal power plants by 2038, a decision which was politically settled—partly due to growing social pressure—after long disagreement. Nevertheless, with "Datteln IV" a newly built coal-fired power plant was put into operation in 2020 [155] which demonstrates the tendency of energy companies to stick with conventional technologies.

(5) Russian invasion of Ukraine.

At the beginning of the war in Ukraine, Germany was highly dependent on oil and especially gas supplies from Russia. Due to this great dependency, the economic sanctioning of Russia could not immediately be implemented in the energy sector, unlike in other sectors, despite the basic political and societal will in Germany. Nevertheless, the event made the public aware of this dependency and all its disadvantages. The necessity of an energy transition towards renewable energy sources was thus given further political and economic emphasis in addition to the environmental justification. Once again, a single event was the trigger for assessing a situation that had already existed for a long time differently than before and triggering actions that had been postponed until then.

Results—categorization of the interactions and interdependences of the different perspectives

In the context of the German energy transition, the distinction between cause and effect is not always unambiguous. The diagram shows the different paths which have had an impact on the transition of Germany's energy system. Interdependencies between the different factors affect actions and reactions and foster developments in other categories or regarding other pillars of the sustainability concept. In the process of understanding and analyzing the German energy transition, we have derived four conclusions from the causes and effects discussed in the previous chapter which abstract general explanations for the sequence of events.

> *Finding 1:*
> *Environmental disasters and other environmental*

incidents have been triggers in Germany's energy transition process.

As shown in Sect. 3.1, with regard to the environmental pillar, we have discussed incidents with high environmental impact as well as long-term effects, such as the impact of air pollution on the use of fossil resources. These incidents and their interactions with the other pillars investigated and discussed in Sect. 3.2 show that there is no sole or direct impact on political or economic decisions. Nevertheless, it can be seen that every environmental incident has pushed the interaction of politics and society. For instance, the smog in the German Ruhr area caused politics to focus on emission targets. The Chernobyl accident strengthened the anti-nuclear movement in Europe. In the same vein, the Fukushima accident was the reason for Germany's nuclear moratorium. These examples illustrate that events with high impact on the environment have not defined the fundamental path of politics or society but have provided decisive impulses. The Fukushima accident and the ensuing moratorium provide a good example of "the straw that broke the camel's back". The Fukushima disaster alone would not have had any consequences if there had not been an ongoing discussion about nuclear energy in Germany. In conclusion, environmental disasters have been triggers, but no (sole) drivers of the process of energy system transition. This conclusion can also be derived from the fact that the accident provoked different reactions from Germany's neighboring countries.

Finding 2:
The sector of energy generation is heavily driven by political regimentation. The developments are mainly influenced by political requirements.

Energy generation and distribution used to be a natural monopoly or oligopoly, due to technical restrictions. Supplying energy at low cost and with high reliability is a crucial economic and societal factor for any country, thus making the government an important stakeholder. In consequence, the political objectives for energy generators and suppliers are not only determined by technical requirements but can be politically and economically motivated. As Sect. 3.1 shows, after World War II the political will in Germany was to support inexpensive and reliable large-scale power plants, with a centralized structure for supply. Once a running system had been installed, large investments into power plants and infrastructures defined the roadmap of energy companies for decades. Similarly, political forces drove the introduction of nuclear power generation. Later, when the transition of the energy system towards sustainability had been established as a political goal, the requirements for generating and supplying energy changed. Politics changed the focus from an inexpensive and reliable energy supply towards a renewable and reliable energy supply, which not only led to some drastic changes from a technological perspective but which also required substantial changes in government subsidies. In parallel, the liberalization of the energy market scheme was established, where more and more rules have been adopted to open up electricity generation to large sectors of the population and to smaller companies. The introduced market rules were enforced by regulations and subsidy schemes introduced by government to support renewable energy generation.

Finding 3:
Political requirements and legal regulations have been determined by macroeconomic and societal demands. Following these factors, the political objectives have undergone a consistent conversion over time.

The aim of politics is to act for a society rather than promoting established structures and companies. Although the political framework supported large-scale energy generation in the first decades after World War II, the tendency towards less harmful emissions and reduced air pollution became apparent in political actions. Already in 1974, air pollution was a topic in Germany's election campaign. At the end of the twentieth century, clear signs of a fundamental change in the energy sector towards more sustainability were recognizable. This change took place despite the fact that Germany is a country with a high demand for electricity, and at the same time with geographically few possibilities for generating renewable electricity from hydropower. From a macroeconomic perspective, the implementation of a market scheme was introduced in 1990 and expanded step by step. This introduction was also an expression of societal demands. The strategy towards the energy transition became more apparent over time. The most important cornerstones were the introduction of a market scheme, subsidies for the generation of electricity from renewable sources, separating energy companies into generators and system operators, and discrimination-free grid access. Furthermore, the Federal Network Agency (Bundesnetzagentur) was established to monitor these targets. Moreover, politics sent another signal towards energy companies with the election of the Green party into the government in 1998. Seven years later, with the re-election of the conservative Christian Democrat government, the political strategy was interrupted by the prolongation of the nuclear phase-out, which was cancelled again after the Fukushima accident and changed towards a shorter phase-out. Leaving out the latter, the political roadmap went steadily in one direction towards the energy transition, in line with societal concerns and demands.

> *Finding 4:*
> *Energy companies followed the tendencies determined by political decisions and regulations, as well as subsidies for a long time, but missed the chance to properly adapt their business models.*

As discussed, the political framework supported large-scale and inexpensive energy generation in the first post-WWII decades. In addition, nuclear power plants were supported politically for a long time. Substantial investments and the oligopoly market structure made energy companies large and inflexible, but this situation was also politically desired. After the first signs of market liberalization, energy companies reacted only slowly to the changing market conditions. This became apparent not only in their focus on large fossil power plants, but also in a hesitant investment strategy towards renewable generation technology. Since the nuclear moratorium of 2011, the companies took legal action to obtain compensation for shutting down nuclear power plants. A similar procedure can be seen with the operation of lignite-driven power plants. Substantial organizational changes were implemented when the corporations' business models eroded and profit numbers fell substantially. In summary, we conclude that the political path towards Germany's energy transition was largely predictable already by the end of the twentieth century, but large energy companies in Germany missed the chance to adapt their business models properly by ignoring long-term changes in societal perceptions and political regulations.

Conclusions and discussion

Discussion of the outcomes and answering the research question

This paper addresses the following research question: *How can the events and effects in the course of the German energy transition be classified with a cause-and-effect analysis and which interactions between the events and effects can be identified?*

Based on our work described above, we can state the following: all four factors described—economic, ecological, societal/political, and technological—have impacted the German energy system transition. The interactions between the influencing factors have shaped the path towards more sustainability of the country's energy system.

We were able to show that political measures and regulations were the decisive drivers of changing the energy market. In turn, political action in this area was influenced by two factors: economic demands on the central element of energy supply and societal demands that had a long-term impact via processes that form opinions in political parties and via election results. Environmental influences alone did not drive the process forward. However, individual environmental accidents along with predictions from science, e.g., the reports compiled for the Club of Rome or climate change reports by the IPCC [156] were either the impulse or the final trigger for social and political processes. It is remarkable that technological developments only had a minor influence as an initiating element in the process of transforming the national energy system. New technologies and business models could only be established with proper political support.

For several decades, the energy companies had relied on operating large centralized power plants. This approach was supported politically and was intensively promoted, especially in the case of nuclear power generation. As the political will shifted towards renewable energy, the framework for generators was gradually transformed. The Electricity Feed Act (Stromeinspeisungsgesetz) of 1990 and the market liberalization of 1998 left the producers mainly untouched, so they stuck to their established strategies. It was not until the Renewable Energy Sources Act [Erneuerbare–Energien–Gesetz (EEG)] in 2000 and the exemption of renewable energies from the Merit Order that the energy companies were affected. At the same time, the nuclear phase-out had been prepared. Despite both developments, the energy companies held on to their sources of revenue and only started to convert to renewable energies after a long delay. Several rounds of amendments to the EEG strengthened the transition of the German energy system towards more sustainability. However, it is also clear that further action is necessary with regard to both achieving the climate change goals and becoming more independent from external sources, as the consequences of the Russian invasion of Ukraine have impressively shown.

Conclusion

The present paper shows influence factors which have been related to the process of energy transition in Germany since World War II. These factors are divided into four categories: the three pillars of sustainability (environment, economy, society) are considered, as well as a fourth pillar of technology. First, the different factors for each category were described in chronological order. In a second step, the four perspectives were integrated in a chronological cause-and-effect analysis for each of the categories. These cause-and-effect analyses, allowed us to investigate the complex interdependencies between the different factors, but also to determine that some factors are individually important, while others are contradictory or supportive of each other. Analyzing the overall picture, this paper shows that each pillar takes on a certain role. The pillar of the economy sets the starting position, which is relevant and valid over a long period. The pillar of society and politics sets the regulative framework for the different actors, based on the perceptions and demand among large parts of society. Hence, this happens by taking singular events into account and via ongoing discourses and interactions between society and politics. Environmental factors trigger the development in politics and society, which leads to changes in the economy. Finally, the pillar of technology is more marginalized in terms of causes and effects on the other pillars than one might expect. The investigations show that technologies provide the opportunities for major changes and improvements, but do not initiate them in the first place. Instead, technologies and their further development fulfill the needs set by new regulations and the economy.

To further understand the transformation process described above, one possibility for further research is to complement our work with the application of the multi-level perspective (MLP) by Geels and Schot (2010) [157]. The methodology helps to take into account the complexities, multi-layeredness and non-simultaneities in transformation processes and at the same time to radically simplify them. Changes and dynamics in three levels of action create a space of possibility for transformations. The model is a helpful analytical grid for discussing transformation processes in a structured way. Another method to proof the results of this paper could be the investigation via the method of a quadruple helix approach. Some suggest to add the fifth element of nature [158] which would change the integration of the environmental pillar. By applying one of these methodologies, the understanding of the German energy transition can be further deepened by taking into account the four perspectives we have identified.

In conclusion, waiting for technological leaps before implementing a fully renewable energy system is not a promising strategy. This study has identified social movements that have translated into political actions and regulations as the main drivers for the energy transition. These movements set an economic environment and defined requirements as well as demands towards the development of technologies. In this vein, energy companies must observe their regulatory and social environment and their stakeholders' will to avoid missing substantial transformations. An enhanced agility of the major utilities is necessary for this to happen. Overall, our cause-and-effect analysis has shown that the entire energy system transition is a complex and path-dependent process, which is driven by multiple factors, and many different stakeholders have significant stakes in the related developments.

Abbreviations

BES	Battery electricity storage
CSR	Corporate social responsibility
EBIT	Earnings before interests and taxes
EEG	Renewable Energy Sources Act (Erneuerbare-Energien-Gesetz)
FNA	Federal Network Agency (Bundesnetzagentur)
GW	Gigawatt
kWh	Kilowatt hour
MW	Megawatt
LNG	Liquid natural gas
NGO	Non-Governmental Organization
NPP	Nuclear power plant
PV	Photovoltaic

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KK and PW designed the underlying model, conducted research for filling it and wrote the manuscript. PL was involved in the ideas and conception. Furthermore, he wrote and revised the manuscript. All authors read and approved the final manuscript.

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