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REVIEW ARTICLE

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The German Energiewende and its roll-out of renewable energies: An economic perspective

Abstract This paper gives a short overview of the German Energiewende, i.e. the transition of a large and mostly thermal electricity system towards electricity generation from renewable energy source. It discusses both, the motivation of the transitions as future goals and current status. Furthermore, it gives an in-depth view into the changes in economic costs for society as well as electricity price effects, especially for average private households and industrial consumers. It also discusses the benefits of the promotion of renewable energies in Germany.

Keywords electricity system, renewable energy, cost-benefit analysis

1 Introduction

Germany was among the first countries to promote large-scale deployment of electricity generation from renewable energy sources (RES) such as wind energy, photovoltaics and biomass. The process picked up speed in the year 2000, when the *German Renewable Energy Sources Act* was introduced. At that time, the underlying technologies were expensive and less developed. In addition to promoting RES, in 2011, the German government also decided to phase out nuclear electricity generation, shutting down all nuclear power stations by 2022. The resulting transition of the German energy system was so drastic that the German term "Energiewende" was adopted by the English-speaking world and the whole process received worldwide attention.

As a result of early RES promotion in Germany, between 45% and 48% of the worldwide installed capacity of photovoltaics was installed in the country between 2006 and 2010 [1]. As for onshore wind, Germany installed about 30% of the total global capacity in 2006. These shares decreased over time due to relatively larger investments in other countries. However, Germany installed a significant amount when RES were less developed and hence significantly more expensive than today. While the associated payments helped to bring down costs for RES due to learning, and now help to push RES investments worldwide, they imposed a significant financial burden on German society. Therefore, the transition of the German energy sector is not only a technological challenge (as is pointed out in several publications in this special issue), it also deeply impacts the economy.

This paper analyses several economic effects of the Energiewende. In particular, it gives a short insight into the costs and benefits of promoting renewable energies in Germany. The data focuses especially on the electricity market. Section 2 explains quantitative political goals of the energy transition and shows the roll-out of RES in the last 25 years. Section 3 explains resulting economic cost effects. Section 4 gives an insight into technology-specific cost developments in the electricity sector, while section 5 shows the expenditures for different consumer groups (private households and industrial facilities) due to levies and surcharges correlated to the energy transition. The benefits of the renewable roll-out are presented in Section 6. Section 7 considers how costs may change, and suggests areas for further research.

2 Political goals and historic goal achievement

The roll-out of RES is politically justified by reasons such as limiting climate change, protecting the environment, internalizing external costs to the environment from

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non-renewable sources, and promoting the development of renewable technologies [2][1]. Further often mentioned goals for the process are the promotion of energy autarchy, job creation, and abandonment of fossil and non-sustainable fuels [3].

The quantitative goals of the Energiewende are as follows: Europe's biggest economy phases-out of nuclear energy by 2022. At the same time, Germany will increase the shares of RES in gross electricity consumption to between 40% and 45% by 2025 and to at least 80% by 2050 (see Table 1). In addition, the German government has established goals for the reduction of greenhouse gas emissions, gross electricity consumption, and other energy variables in many sectors by 2050.

These goals have changed over time. Mostly, they have increased. For example, the actual goal for 2020 is that renewable energies will hold a 35% share in the total electricity consumed, but this goal has previously been significantly lower. In 2005, the German government introduced a goal to produce 20% of Germany's electricity from renewable sources by 2020 [8]. This goal was already achieved in 2011 [5]. In 2008, due to a rapid rise in the number of renewable installations, the government set an increased goal of at least 30% by 2020 [9]. That goal was reached in 2015 when approximately 32% of German gross electricity consumption was supplied from renewable energies [5]. Hence, Germany has a certain credibility in achieving its ambitious environmental goals, especially with respect to electricity generation from RES.

This can be confirmed by looking at the technology-specific roll-out of RES since 1990 (see Fig. 1). In the early 1990s, the installed hydro power capacity made up more than 80% of the renewable capacity. In the decade from 1990 to the end of 1999, especially the installed capacity of wind power increased to 4400 MW. By the year 2000, Germany started to profoundly support and subsidize various renewable technologies. The data showed that directly following the implementation of the *Renewable Energy Sources Act* in 2000, onshore wind, in particular, was installed and the wind installation capacity nearly quadrupled between 1999 and 2004. Installations of photovoltaic systems did not rise significantly until 2005 but increased to a great extent from 2009 to 2012. Biomass increased steadily and had a share of about 15% of

Table 1 Selected goals of the German government in the field of energy policies [4–7]

Year	η/%	δ_{gc}/%	δ_p/%	δ_{ge}/%	D/%	N	δ_h/%
2000	6.2	–	–	0	–	–	–
2015	31.6	–4.0	–7.6	–27.2	+ 1.3	25502	–11.1
2020	⩾35	–10	–20	⩾ –40	–10	1000000	–20
2025	40–45						
2030	⩾50			⩾ –55		5000000	
2035	55–60						
2040	⩾65			⩾ –70			
2050	⩾80	–25	–50	⩾ –80 to –95	–40		

Notes: η—share of renewable energies in electricity consumption; δ_{gc}—reduction of gross electricity consumption compared to 2008 figures; δ_p—reduction of primary energy consumption compared to 2008 figures; δ_{ge}—reduction of greenhouse gas emissions compared to1990 figures; D—development of final energy consumption in transport compared to 2005 figures; N—number of electric vehicles; δ_h—reduction of heat demand (buildings) compared to 2008 figures

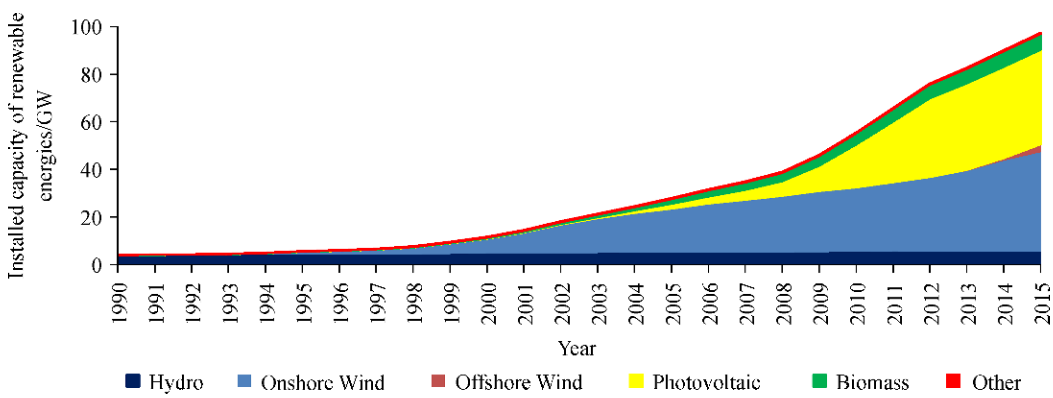

Fig. 1 Installed capacity of renewable energy in Germany since 1990 [5]

1) The *Renewable Energy Sources Act* is updated regularly to keep pace with market changes.

installed RES capacity in Germany in 2015. The installed capacity of hydro power remained relatively constant over time. Due to the increase in other technologies, its relative share decreased continuously. In 2015, hydro power capacities made up 5.6 GW, which accounted for about 6% of Germanys RES capacity. For the same year, about 84% of installed RES capacity was either from onshore wind or from photovoltaic systems. The combined installed capacity of these two technologies amounted to about 80 GW, with about half of that capacity coming from each technology. Offshore wind had 3 GW capacity [1]. This was significantly below the other two technologies but Germany still had the second highest installed capacity of offshore wind worldwide in 2015 (after the United Kingdom).

3 Economic costs

The steep increase of installation rates, especially of wind energy and photovoltaics, which was supported by the feed-in tariff system of the *Renewable Energy Sources Act*, brought additional costs for society and especially for electricity consumers. Increased costs resulted from the high costs attached to those new and climate-friendly renewable technologies. Three important cost parameters can be evaluated to better understand the economic effects of providing financial support for RES in Germany: Gross Costs, Market Values and Renewable Energy Support Costs.

First, the support for renewable energy in the *Renewable Energy Sources Act* includes significant payments to RES generators to address the fact that most RES, having higher levelized costs of electricity production, are not competitive in the electricity market. Therefore, Germany established technology-specific remuneration for renewable electricity production (feed-in tariffs), which were determined *ex-ante* by government administrations in € per kilowatt hour. These feed-in tariffs were usually paid for 20 years plus the year of installation and fixed above wholesale market prices. The overall payments can be referred to as the Gross Costs of RES. For the last four years (2012 to 2015), these always exceeded € 20 billion per year, with € 27.5 billion in 2015 being the highest value so far [10].

Secondly, the electricity produced by RES has a Market Value. This value equals the product of RES electricity generation and the wholesale electricity price. The wholesale electricity price is determined on wholesale markets such as the European Power Exchange (EPEX) in Paris. The wholesale price is derived from producers selling electricity to consumers, who are mostly aggregated, e.g., via municipalities.[1)] Wholesale prices often differentiate by the hour, i.e., different hours have different prices. The market values for all the electricity produced from RES supported by the *Renewable Energy Sources Act* amounted to approximately € 4.7 billion in the year 2015 [10].

As the (hourly) Market Value of RES is the product of (hourly) wholesale prices and (hourly) RES generation, it depends on both factors. However, wholesale prices and electricity generation from RES are not independent: The more energy is produced from (intermittent) RES, which have near-zero marginal costs of production, the lower the wholesale price tends to be (*ceteris paribus*). Hence, RES electricity production and wholesale prices are negatively correlated. Therefore, the so-called market value factor of RES, which shows the average value of electricity produced by renewable energies in relation to the average annual electricity price, decreases when additional intermittent RES enter the system [11]. While the electricity production of the first installed photovoltaic systems had a market value above one, as it was produced during high-priced, peak period during daylight hours, this is no longer true. Due to more and more supply from photovoltaics during daylight hours, electricity prices for the power generated at this time have decreased in recent years. This has lowered RES market values. As a result, the market value factor of photovoltaics decreased from 1.06 to 1.00 between 2012 and 2015 (authors' own calculation with data from [12]). In the same period, the market value of onshore wind declined from 0.89 to 0.86.[2)] Despite the reductions in market values generated by RES, the fixed feed-in tariff still compensates for every kWh produced.

Finally, the difference between Gross Costs and Market Value can be interpreted as Renewable Energy Support Costs (RESC)[3)]. These costs, in addition to the market value, are the costs necessary for installing and operating RES. They are the additional costs incurred for producing "green electricity" instead of the electricity from conventional sources. Figure 2 shows the development of RESC in Germany. The costs increased in recent years to more than € 20 billion annually and reached ca. € 22 billion in 2015. Out of these € 22 billion, the electricity generated from photovoltaics received 44% (€ 9.6 billion), onshore wind energy 21% (€ 4.6 billion), and biomass 28% (€ 6.1 billion). Offshore wind energy, hydro power and further minor technologies received 7% (€ 1.6 billion).

1) Note that the underlying product is electricity. This electricity can come from all sources, for example, from both RES and conventional power stations.
2) This effect is also referred to as self-cannibalization of renewable energies.
3) In practice, three additional components influence RESC: (1) avoided use of grid charges; (2) the costs of the "Privilege of Green Electricity" ("Grünstromprivileg"). (However, they are relatively small in comparison to the numbers shown in the graph); and (3) the costs paid by electricity consumers for RES. (These costs are fixed for one year in advance to provide planning certainty for both consumers and retailers. The difference between forecasted costs and actual costs is balanced in later years. This effect shifts costs or gains caused by inaccurate estimations from one year to another, but the effect is also relatively small).

4 Technology-specific cost developments

As the earlier analysis has shown, the German energy transition is mostly driven by onshore wind and photovoltaics. There are two reasons for the large penetration of these two technologies. First, both onshore wind and photovoltaics are cheaper today than other renewable technologies, such as, e.g., biomass or offshore wind, due to their recent, steep cost reductions [13–15]. Second, despite the huge current roll-out of onshore wind and photovoltaics, both technologies still have huge amounts of unused technical potential in Germany. In comparison, the German Federal Network Agency attributes both hydropower and biomass lower unused technological potential [16].[1)]

Figure 3 shows the development of feed-in tariffs for onshore wind turbines and small-scale photovoltaic systems for the period from 2000 to 2015. The feed-in tariff shown is the payment per kWh which a newly-installed facility receives when starting production in that year. The feed-in tariff is usually paid for 20 years plus the remainder of the year of installation.

Figure 3 shows that photovoltaic plants starting operations in the year 2000 received around € 0.50 per kilowatt hour. Following that, tariffs were even increased by regulators in 2004 to accelerate the roll-out. Afterwards, between 2004 and 2015, tariffs for photovoltaic systems show a steep decline, from € 0.57 per kilowatt hour ten years ago to approximately € 0.13 per kilowatt hour in 2015. Therefore, new small-scale installations of photovoltaics received only 22% of the feed-in tariff from installations built a decade ago. For reference, this feed-in tariff can be compared with the current wholesale price of about € 0.035 per kilowatt hour. Alternatively, they can be compared with the total cost of new coal or gas fired capacity which, depending on fuel prices, cost of investment and CO_2 emission, is roughly at € 0.06 per kilowatt hour.

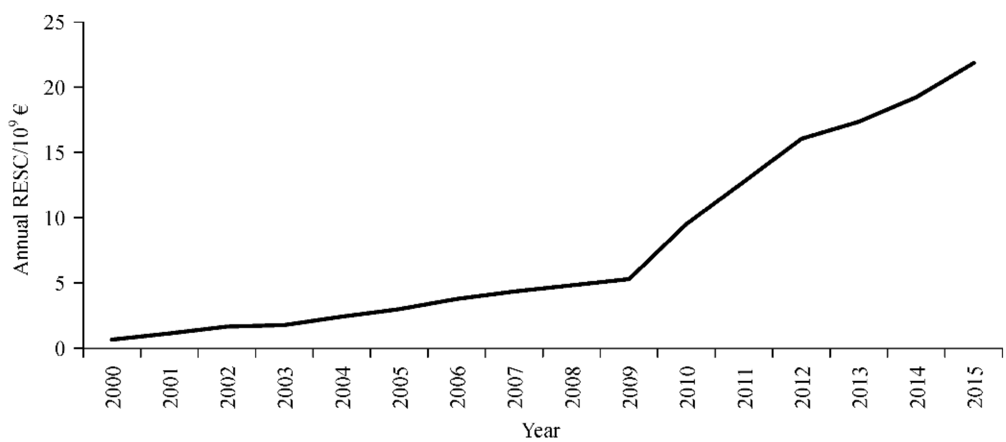

Fig. 2 Annual renewable energy support costs (RESC) of subsidized renewable energy sources in Germany [10]

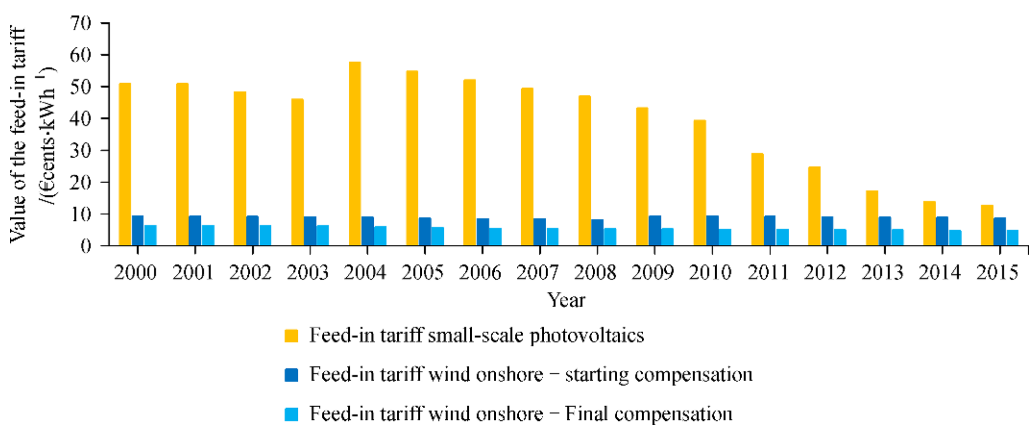

Fig. 3 Feed-in tariff development for small-scale photovoltaic systems and onshore wind [17]

1) Reference [16] gives scenarios for the grid extension plan in Germany, which shows possible roll-out scenarios for different RES technologies in the next two decades.

The feed-in tariff scheme for onshore wind is slightly more complicated as it consists of a high starting compensation payment and a lower final compensation. The development of both tariffs can be found in Fig. 3. At least for the first 5 years of the 20-year period of feed-in tariff payments, all onshore wind energy plants will receive the higher starting compensation. For how much longer the starting compensation will be paid to a specific wind turbine is related to its expected wind yield or, being more specific, of the relation to a fixed yield of a so-called “reference location” with a specific height and wind speed, which is fixed at 100%. The extension of the starting compensation relates to the difference between the specific situation and the reference yield of the wind plant. Therefore, the average feed-in tariff of a wind turbine in Germany does not just depend on the year of installation, but also on the specific wind yield. Wind turbines with a very low wind yield get the starting compensation for the whole period of 20 years. The purpose of this regulation is to strengthen financial support for wind installations in less profit-yielding regions and thereby support a more regionally distributed wind energy development. Compared to photovoltaics, the value of the feed-in tariff for onshore wind has remained relatively stable (see Fig. 3). While the starting compensation decreased from about € 0.091 per kilowatt hour in 2000 to € 0.085 per kilowatt hour in 2015 (–7%), the final compensation decreased from about € 0.062 per kilowatt hour to about € 0.046 per kilowatt hour (–26%).

5 Customer expenditures

To finance the additional costs of renewable energies, i.e., the RESC of more than € 20 billion per year discussed above, German electricity consumers pay a fee per kilowatt hour consumed (renewable surcharge). In principle, all consumers, industrial, commercial, and domestic pay this surcharge for every kWh consumed. However, the fee is significantly reduced for consumption by energy-intensive companies. This discount was introduced to avoid a reduction in competitiveness of industries in international markets (where companies from other countries tend to have lower electricity prices and, in particular, lower RES support fees). As a consequence, the cost distribution between different types of consumers is not proportional to their consumption.

Figure 4(a) gives the proportion of electricity consumed by certain sectors in Germany. The industrial sector consumes almost half, while private households consume only one quarter. Compared to Fig. 4(a), Fig. 4(b) shows the shares of the predicted RESC (€ 21.8 billion for the year 2015) paid by respective consumer groups. More than one third of the costs, the greatest share, are paid by private households (€ 8.1 billion), while industrial customers, the heaviest consumers, just pay 30% (€ 6.6 billion). 17% of the costs are paid by commerce, trade and services (€ 3.8 billion). Public institutions paid € 2.6 billion, while the agriculture and transport sectors have a minor burden of € 500 million and € 200 million respectively. These payments are part of the electricity price (in € per kilowatt hour). Therefore, supporting renewable energies in Germany increases electricity prices to the consumer. As households and industrial consumers pay different fees and have different costs, such as with respect to network charges, these two groups will be analysed separately.

Figure 5 illustrates the development of electricity prices for the average German private household in € per kilowatt hour since 1998. As can be seen from Fig. 5, all cost components increased. However, especially in recent

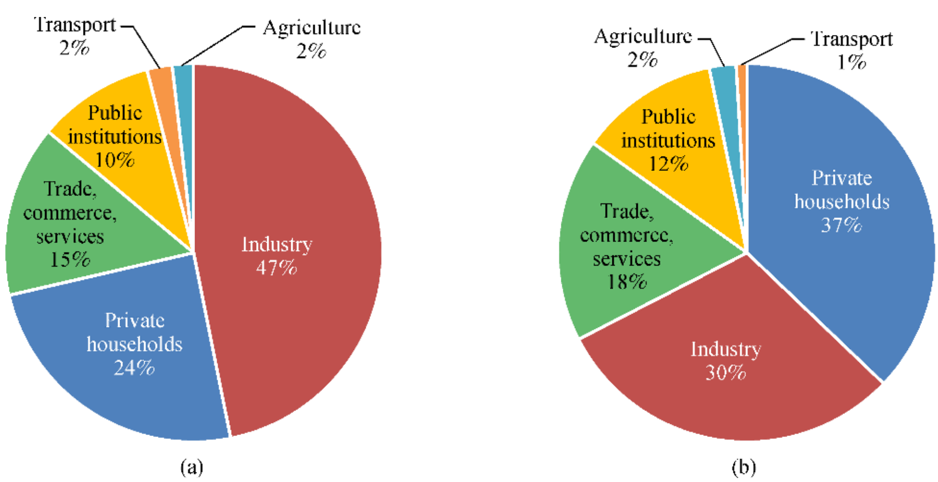

Fig. 4 Share of electricity consumption (first circle) and share of RESC burden (€ 21.8 billion) (second circle) paid by different consumer groups in 2015 [18,19]

(a) The proportion of electricity consumed by certain sectors in Germany; (b) shares of the RESC (€ 21.8 billion for the year 2015) paid by respective consumer groups years, the costs for the promotion of renewable energies rose significantly. In 2015, the household price was about € 0.29 per kilowatt hour. This price included all cost components, in particular costs of electricity generation, grid costs, wholesale and retail costs, the renewable surcharge as well as all other taxes, fees and expenses. In 2015, the renewable surcharge amounted to € 0.062 per kilowatt hour (about 22% of a customer's average price for electricity). If further costs associated with the general process of transforming the energy sector in Germany were accounted for, the value rose to approximately € 0.064 per kilowatt hour), represented by the green section. In addition to the renewable surcharge, this value included the costs for the promotion of combined heat and power plants (CHP), as well as the offshore wind liability levy. A comparison of German household electricity prices with other countries showed that for the year 2015 Germany had the second highest electricity prices in Europe, after Denmark [20]. The European Union average, comprised of 28 European countries, was approximately € 0.21 per kilowatt hour, about 25% lower than German prices.

Figure 6 depicts the electricity prices for industrial consumers. The cost of generation, grid and retail fees (black section) declined in recent years to only slightly higher than 15 years ago. Although the trend in cost to industrial consumers is comparable to the prices for households, a higher percentage of the energy costs of the industrial sector are attributable to the energy transition (green section). During the last three years (2013 to 2015) more than 35% of industrial electricity prices have been related to financial measures supporting the energy transition, reaching 44% in 2015. In the year 2000, when the *Renewable Energy Sources Act* was first implemented, only approximately 5% were related to that component. Now, compared to other European Union nations, German industrial electricity prices are one of the highest. While Italy and the United Kingdom are the only big economies with slightly higher prices, for industrial consumers, the average cost within the European Union is € 0.12 per kilowatt hour, approximately 11% lower than German prices [20].

6 Economic benefits

The large scale roll-out of renewable energies in Germany (Section 2) is responsible for the economic costs discussed in Sections 3, 4, and 5, but it also leads to several benefits. Numerous papers have been published in recent years which evaluate and quantify various economic benefits resulting from RES. Some of these consider the German context, others have an international perspective. Although

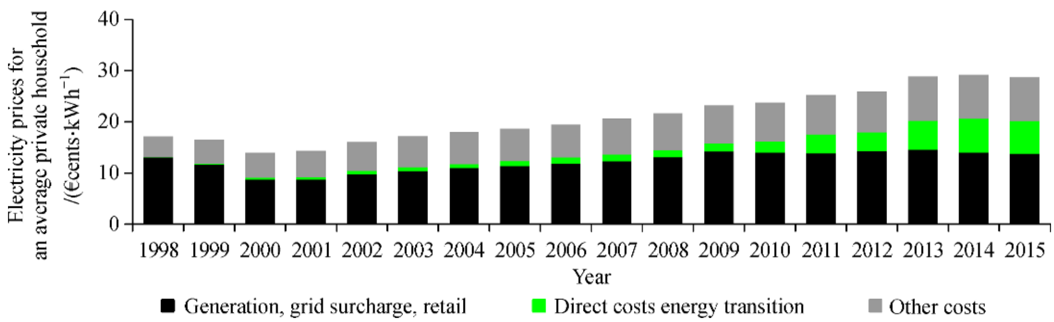

Fig. 5 Electricity prices for an average German private household for the years 1998 to 2015 [19] (Green sections represent the direct costs of the energy transition: renewable surcharge, CHP surcharge, offshore liability levy; black sections represent the costs of electricity generation, grid surcharge, wholesale and retail costs; grey sections represent all other costs: e.g., further surcharges and taxes.)

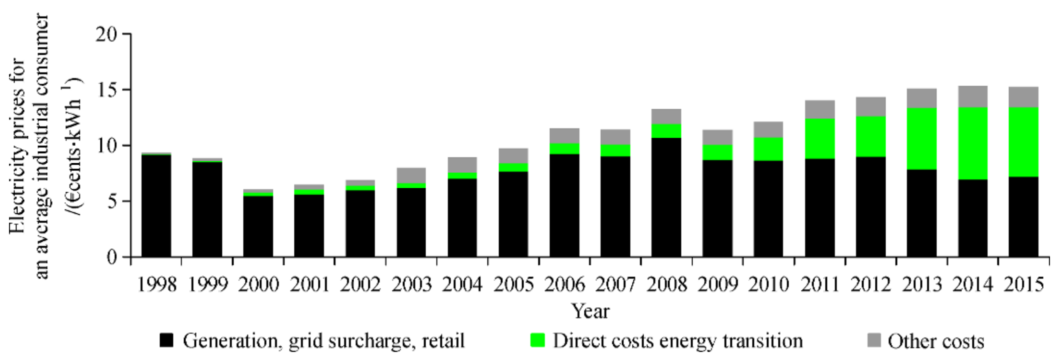

Fig. 6 Electricity prices for an average industrial consumer in Germany for the years 1998 and 2015 [19] (Green sections represent direct costs of the energy transition: renewable surcharge, CHP surcharge, offshore liability levy; black sections represent the cost of electricity generation, grid surcharge, wholesale and retail cost; grey sections represent all other costs: e.g., further surcharges and taxes.)

there is a debate regarding which elements are useful benefits of a renewable roll-out [21,22], the following benefits are widely discussed and often mentioned in the German case: correction of negative environmental externalities related to fossil fuels; correction of research and development (R&D) externalities (i.e., market participants invest too little in RES as other companies copy advances); reduction of primary fuel imports; and effects on employment.

RES reduce negative environmental externalities. In contrast to electricity generation from fossil fuel combustion, RES do not contribute to global warming in a meaningful way and emit significantly lower levels of harmful substances such as particulate matter (respireable dust), NO_x and SO_2.

Furthermore, there are externalities for investment in R&D, which result from the spillover effects of investment in R&D: any single company investing in R&D also provides knowledge to other companies both within the country and beyond. However, as any company deciding on R&D is not taking these spillover effects into account, which are positive from an economic perspective, R&D investment is inefficiently low. Hence, German RES support corrects these externalities.

Furthermore, Germany has a high import dependency on energy resources. The majority of hard coal (89% of domestic consumption), natural gas (89% of domestic consumption), Uranium (100% of domestic consumption), and oil (99.5% of domestic consumption) are imported from other countries [6]. The two noteworthy exceptions are the greenhouse gas emission intensive lignite stock and climate friendly RES. Both are produced within Germany, and the import share for each is 0% of domestic energy production, with exception to some elements of imported biomass, like bioethanol or palm oil. A high import dependency has at least two disadvantages: the first is the costs of resources imported, and the second is a higher risk of supply interruption. The total amount of costs for German energy imports was 90 bn € in 2015 [23]. This number is heavily influenced by fluctuating costs for oil imports which have a share of more than half of the total. In comparison, about 8.8 bn € of primary fuel import costs were avoided for the year 2015 due to renewable energies (including renewable technologies for heat and transport) [6].

In the year 2015, three hundred and thirty thousand people were employed directly or indirectly because of renewable energies in Germany [6].[1] This is referred to as gross employment effect. However, when evaluating the effect of the aforementioned RESC on employment, the net employment effect of RES is more important. Estimating the net employment effect takes into account the influence of additional RES employment and associated RESC on other employment capabilities. These might result from replacing other energy resources and their value added (e.g., coal or gas). Those energy sectors most likely lowered their investment activities and therefore suffered employment losses in comparison to a counterfactual scenario without (or at least lower) RESC. Furthermore, purchasing power is reduced owing to higher electricity prices for consumers (see Section 5). Finally, the overall employment effect depends on the factor intensities of labor and capital in renewable on the one hand and thermal power generation on the other hand. The net employment effect seems relatively small in comparison to the aforementioned RESC of € 22 billion in 2015. Reference [24] estimate that in 2010, between 44000 and 72000 jobs can be calculated as positive net employment effects for Germany. References [25,26] show comparable results for 2015 with 50000 and 10000 jobs created. Conversely, Ref. [27] estimates even negative net employment effects, which would mean that more workplaces are vanished than created by the support of RES.

7 Conclusions and outlook

Germany is one of the first countries that have invested heavily in renewable technologies such as wind, photovoltaics and biomass. This support is effective: both installed capacities and energy production from RES have increased significantly. However, the efficiency of RES promotion is limited. One reason for this is that the support scheme does not focus on the cheapest renewable technologies. Instead, high, specific feed-in tariffs have promoted investment in relatively expensive technologies such as early photovoltaic systems and biomass.

The steep increase in total installed RES capacity, in combination with this inefficiency, has led to high economic costs: the gross costs of RES amounted to € 27.5 billion in 2015 and the produced electricity had a wholesale market value of € 4.7 billion. Hence, the 2015 RESC amounted to approximately € 22 billion, after further deducting avoided use of grid charges by RES, caused by their avoided electricity feed-in in higher grid levels. This amount of renewable energy support costs is the additional cost of producing 161 TWh from RES in 2015, as opposed to from other energy sources.

Due to the framework of the RES support system, which guarantees most RES installations feed-in tariff payments for twenty years plus the year of installation, short-term reductions of RESC for German consumers are unlikely. However, cost reductions will occur when old and expensive renewable installations leave the current support mechanism. This effect, which will start in the year 2021 at the latest, will reduce the costs of consumers.

In terms of advantages, German investments in renewable energies compensate negative externalities on the

1) Compared to 800000 currently employed in the German automobile industry.

environment, in particular pollution and global warming. Furthermore, the support scheme compensates externalities in research and development, import dependencies for primary energy imports are reduced and net employment levels may improve slightly.

The question by how much German RES investment helped global climate protection by financing learning effects resulting from the high number of domestic installations, most likely in the photovoltaics sector is left for further research. Furthermore, a quantification of benefits and the final comparison of costs and benefits ("Was it worth it?") are also left for further research.

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