Advanced Review

Trends toward 100% renewable electricity supply in Germany and Europe: a paradigm shift in energy policies

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In industrialized countries such as Germany, electricity production contributes 30–40% of the greenhouse gas (GHG) emissions of the country. Confronted with GHG emission reductions targets of 80–95% by 2050 and with some GHG emitting sectors confronted with great difficulties to reach such targets, such as agriculture, the power sector will need to reduce its GHG emissions virtually to zero. As nuclear energy involves very substantial accident risks and the unsolved problem of safe long-term deposit of nuclear waste and as carbon dioxide capture and storage (CCS) has rather limited safe storage potentials at least in Europe, the question arises, whether it will be possible to supply 100% of all necessary electricity from renewable energy sources? We show that a fast expanding volume of analyses underlines the feasibility and reliability of 100% renewable electricity supply systems. This fast mounting evidence appears to mark the beginning of a paradigm shift in energy politics, as highly regarded national and international advisory bodies such as the IPCC or the German Council of Environmental Advisors start to adopt this perspective. The example of the highly publicized study of the German Council of Environmental Advisors shows how a 100% renewable electricity system for Germany, Europe, and North Africa could look in 2050 and how the transition toward such a system could be achieved. This study, conducted with major input from the authors, is used to show the major aspects of a 100% renewable electricity supply system, such as the security of supply in every hour of the year, the compensation of intermittent sources such as wind and solar PV energy by other renewables and expanded storage, and the necessary extension of national and international grid infrastructures.

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INTRODUCTION

Anthropogenic climate change has reached such an extent that international organizations such as the Intergovernmental Panel on Climate Change (IPCC) are calling for substantial reductions in greenhouse gas (GHG) emissions.[1] By 2050, global GHG emissions should be roughly cut to 50% of the emission level of the year 2000. It is international consensus that such a reduction needs to be achieved with differentiated responsibilities.[2] The IPCC suggests emission reductions in the range of 80–95% for industrialized countries by 2050[3]. As carbon dioxide emissions from the use of fossil fuels are by far the largest contribution to anthropogenic GHG emissions (see Ref 1, p. 4), the use of fossil energy is a prime target for the necessary GHG emission reductions.

The CO_2 emissions from electricity generation contribute a major share to global and national GHG emissions (see e.g., Ref 4, p. 4 or Ref 5, p. 143). In countries such as Germany, emissions from

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electricity generation may constitute up to one third of the national GHG emissions (Ref 5, p. 148). Different from other sectors such as agriculture or some industries (e.g., cement production), there are CO_2 free production options for electricity generation. These are mainly through the use of renewable energy sources such as wind or solar power. Nuclear power is often seen as CO_2-free, nevertheless, detailed life cycle studies show that there are life cycle CO_2 emissions associated with the use of nuclear power (see e.g., Ref 6 or Ref 7). A major reduction of CO_2 emissions from power plants is also possible by using carbon dioxide capture and storage technologies (CCS), although this is not CO_2-free. The CO_2 from the fossil fuel is still produced, but about 90% can be retained and stored in underground formations such as saline aquifers or old gas fields. As the process increases the total necessary energy input per kWh of electricity produced, it does increase the emissions of all other pollutants accordingly (see Ref 8). Unfortunately, the gas volume to be stored is very large (about 5 million tons of CO_2 per year for a 1 GW coal-fired power plant). At the same time the available save long-term storage capacities appear to be rather limited at least in Europe, allowing for only a few decades of storage in countries such as Germany, if most CO_2 from the use of fossil fuels is captured and stored[9]. Thus, CCS is not a long-term option for a carbon-free electricity supply. Furthermore, Lund and Mathiesen[10] show that CCS does not fit into the transition toward a 100% renewable electricity supply, which will be the option in the long run, even if CCS would be used as a bridge technology. Since the severe accidents of Chernobyl and Fukushima, nuclear power has proved to be a rather risky option and is met with strong public resistance in many countries, especially in Germany.

As neither CCS nor nuclear power are sustainable solutions of the problem, the question remains, whether renewable energy sources can deliver a long-term sustainable, low risk, and climate friendly electricity supply, allowing to fully substitute the use of fossil fuels and nuclear energy even in countries with a rather limited supply of renewable energy sources, high energy consumption, and high population density such as Germany, which has a population density of 229 cap/km^2 (Ref 11) and an electricity consumption of 6200 kWh/cap (calculation based on Ref 12, Table 21).

If a 100% renewable electricity supply is possible, this could be the solution to both problems, the very large contribution of electricity production to climate change and the remaining risks of nuclear power plant operation. Such electricity supply has to meet all electricity demands at every second of the year. If this is possible, the cost of such electricity supply is still an important question to be answered. Even if such a renewable electricity supply may be a low-cost option in the long run, it is still of great concern how much a transition to such a renewable electricity system will cost and how it can be actually achieved?

These questions have been addressed by a growing number of international studies. Since 2010, even highly renown national and international advisory bodies such as the IPCC[13] and the German Council of Environmental Advisors[14] have taken a rather positive position on a central contribution of renewable energy sources to the future world energy supply[13] or even a 100% contribution to the electricity supply of Germany, Europe, and North Africa.[14] Some governments, such as Denmark or Germany, have followed these developments by adopting very ambitious targets for the long-term use of renewable energy sources, while even the EU Commission considers the possibility of a 97% renewable electricity supply for Europe by 2050 (Ref 15), marking the beginning of a fundamental paradigm shift in energy policy.

EVOLUTION OF SUGGESTIONS FOR THE LARGE-SCALE USE OF RENEWABLES

Phase I: 1975–1997

Suggestions for the large-scale use of renewable energy sources, claiming that a 100% renewable energy or at least electricity supply is possible have been made as early as 1975, when Sørensen[16] suggested that Denmark could supply its future energy needs on the basis of wind and solar energy. Such future energy system increases its energy efficiency and relies on hydrogen as major storage option. Two years later in 1977, Amory Lovins published his ground breaking book ‘Soft energy Paths’[17] during a time when the massive expansion of nuclear energy dominated the energy policies of many industrialized countries. Lovins suggested an energy future based on efficiency and renewable energy, which gave orientation to many people critical of the officially planned vast expansion of nuclear capacity—an energy policy, which was typically argued for by the threat of blackouts without the planned nuclear expansion. In Germany, this threat was first voiced by the head of state of Baden-Württemberg Hans Filbinger in his inaugural address in 1975 when he claimed that without building more nuclear power plants ‘the lights would go out’.[18] Lovins’s idea was based on rather rough calculations for the United States, which were more a general outline of a renewable energy future than a serious analysis with detailed calculations. Nevertheless, it proved to be one of the most influential publications on energy in its time. In 1978, Bruckman published his solar vision of the future.[19] Like Lovins, he put this in contrast to a nuclear energy future. Still, his book was more a description of the renewable energy technologies and some energy system vision than a detailed plan of how such future could be achieved. At the end of the 1970s, studies put a greater emphasis on energy efficiency such as Leach[20] for UK or Krause et al.[21] for Germany. From 1985 to 1986, the Bornholm Green energy island project was developed in Denmark and a first detailed hourly system analysis was conducted for the green electricity supply of the island of Bornholm.[22,23]

Phase II: 1998–2009

It took until 1998 for the first detailed analysis of predominantly renewable energy supply scenarios to be published. The LTI-Research Group, a consortium of 24 researchers from eight European institutes and consulting firms, including Sørensen, the author of Ref 16, presented two renewable energy scenarios for the EU15 for the target year 2050, both of which reduced the CO_2 emissions of EU15 by at least 80%.[24] Different from its predecessors, this study looked in detail into the matching of supply and demand. It relied heavily on the reduction of future energy demand and matched the remaining demand with renewable energy sources exclusively from the EU15 territory. In the 'sustainable scenario', the study relied heavily on lifestyle changes and a dematerialization of production to reduce the future energy demand. In 2050, in this scenario 95% of the total energy demand was covered by renewable energy sources, whereas about 5% of mineral oil products were used mainly in the transport sector (Ref 24, p. 96). In the 'fair market scenario' external costs were introduced into the decision on future energy supply choices, which resulted in a share of about 80% of renewable energy sources (Ref 24, p. 156). Both scenarios relied on a large share of biomass to balance the electricity supply of wind and solar energy as well as to supply liquid fuels for the transport sector.

In 1999, Lovins and Hennicke[25] published their factor-four-strategy for a sustainable energy policy. In their rather sketchy global scenario, they claim a share of about 95% renewable electricity for the target year 2050, while it remains unclear how such share could actually be achieved, in detail.

In 2003, a German–Japanese consortium published a study commissioned by Greenpeace International on a 100% renewable energy supply for Japan[26], which followed in the footsteps of the LTI-Research Group (Ref 24), as it looked at drastic improvements in energy efficiency as well as into the details of supplying all sectors with 100% renewable energy. It analyzed the matching of the electricity supply and demand on an hourly basis. The study showed 'how a combination of the best energy efficiency technologies available today, and a massive investment in renewable energy, could ultimately provide Japan with 100% of its energy needs from renewables—including transportation fuels—without expensive and environmentally damaging imported fossil and nuclear fuels' (Ref 26, p. 2).

In 2006, Gregor Czisch published his PhD thesis on a 100% renewable electricity supply for Europe and North Africa.[27] It was the first detailed hourly calculation matching renewable energy supply options, possible storage and electricity demand in the area. He demonstrated that it is possible to match supply and demand on a yearly basis, but that security of supply can be guaranteed in every hour of the year. As he looked at a very large region (Europe up to the Russian border and North Africa extending to the summer wind regime area, south of the Saharan dessert), his results are dependent on the political stability of the entire region, which can be considered the main weakness of his scenario. In the same year, Hendrik Lund published his analysis of an optimal mix of the different fluctuating renewable energy sources for the electricity supply for Denmark.[28] Covering a broad range of renewable shares of up to 100% of the Danish power supply, he showed that the share of solar PV and wave power should differ depending on the total share of renewable electricity in the Danish power supply, but he suggested that further analysis was necessary on more flexible energy supply and demand options as well as the integration of power supply and the transport sector. In his publication 'Renewable energy strategies for sustainable development',[29] Lund showed how the Danish energy supply can be covered 100% by renewable energy sources by 2036. In the same year, the Danish Association of Engineers (IDA) conducted a rather comprehensive study of a 100% renewable energy system for Denmark, which included an hourly system analysis and relied on the input of about 1600 engineers. The results and methodology of this study are described in Ref 30.

In 2008, the Norwegian environmental NGO Belona published its scenario on a global strategy to combat climate change,[31] which claimed that by 2050 90% of the global power supply can be covered by renewable energy sources (Ref 28, p. 11). Unfortunately, this claim is only roughly substantiated on the basis of annual figures for supply and demand. Thus, it did not reach the scientific level of the publications of the LIT-Research Group,[24] Czisch,[27] or Lund.[28,29]

In 2009, Sovcool and Watts[32] published their article 'Going completely renewable: Is it possible (let alone desirable)' in The Electricity Journal. In a rather basic analysis looking solely at the aggregate demand and the generation potential of renewable energy sources, they showed that it should be relatively easy to supply New Zealand as well as the United States totally with renewable electricity. In the same year, Jacobson and Delucchi published an article in Scientific American[33] claiming that the world total energy supply can be covered by renewable energy resources. Compared to the studies by the LTI-research group[24], Lund,[29] or Czisch,[27] both articles, Refs 32 and 33, are rather rough analyses, but Sovacool and Watts (Ref 32) covered the United States and New Zealand for the first time and Jacobson and Delucchi (Ref 33) covered the total world energy supply, whereas the more in-depth studies only dealt with Europe, Europe and North Africa or Demark.

Phase III: 2010 until Today

The year 2010 sees the publication of nine most detailed studies suggesting a 100% renewable electricity supply for a number of different countries. For the first time, detailed hourly simulation studies are published by authoritative national bodies such as the German Council of Environmental Advisors[34] and the German Environmental Protection Agency (Umweltbundesamt),[35] while numerous other organizations such as the European Climate Foundation (ECF),[36] the European Renewable Energy Council (EREC),[37] the German Forschungsverbund Erneuerbare Energien (FVEE),[38] or even international consulting firms such as PWC[39] publish detailed studies on 100% renewable electricity supply options by 2050. In 2010, the Centre for Alternative Technology[40] publishes its proposal for a 100% renewable total energy supply for the UK and Lund publishes his doctoral thesis (Ref 41) showing the feasibility of a 100% renewable energy supply. Beyond Europe only Mason, Page, and Williamson[42] publish a detailed study on the possibility of a 100% renewable electricity supply for New Zealand, based on a supply simulation at the level of half-hour steps. Thus, in Europe the year 2010 seems to mark the beginning of a new awareness for the serious possibility of a 100% renewable electricity supply, even by public authorities and international consultancies as a major step toward effective climate change mitigation. By then, specifically in Germany the idea has left the pure scientific discussion and has become a visible and broadly accepted option in the public debate on the future development of the energy system.

In 2011, this trend is broadened by 10 further studies on the possibility of a 100% renewable electricity or even energy supply. Among these are the extended version of the study by the German Council of Environmental Advisors[43] published in January 2011 only a few weeks before the Fukushima nuclear accident, the Special Report on Renewable Energy Sources, and Climate Change Mitigation by the IPCC,[13] giving a very broad and in-depth review of the central role renewable energy sources need to play for climate change mitigation, and the Energy Roadmap 2050 of the EU Commission,[15] which suggests different scenarios for decarbonization of the European energy supply. One of the scenarios of the Energy Roadmap relies on 97% renewable electricity by 2050 (Ref 15, p. 8). With this official document of the EU Commission, the option of an almost exclusive renewable electricity supply has become a serious option for the European energy policy. This development is underscored by additional publications on a 100% renewable electricity supply by Czisch[44] (Europe and North Africa), Glasnovic and Margeta[45] (Europe), and Krajačić et al.[46] (Portugal),with most of the scientific studies moving toward an analysis based on hourly simulations of supply and demand. In the same year, the World Wildlife Fund for Nature (WWF) publishes its Energy Report[47] based on an analysis done by ECOFYS, which details how the total electricity demand of the world can be met 100% and the world energy demand 95% by renewable energy sources by 2050. Jacobson and Delucchi[48,49] publish an extensive two-part article on the possibilities to supply 100% of the total world energy demand based on wind, water, and solar energy. This work is based on an article by Hart et al.[50], who used a stochastic approach to determine the ability of a state (California) to meet 99.8%, hour by hour for 2 years, based on a combination of wind, solar, hydroelectric, and geothermal energy. In their publication (Refs 48 and 49) Jacobson and Delucchi substantiate their claim made in their 2009 publication (Ref 33) with more material and detailed calculations. Connolly et al.[51] publish a study on a 100% renewable energy system for Ireland, whereas Liu et al.[52] publish an analysis of the potential of renewable energy systems in China.

In 2012, the trend for an extensive treatment of the potential transition to a 100% renewable energy supply continues at a high level. Five new studies are published on European countries [Ćosić et al.[53] (Macedonia), Silvestrini[54] (Italy), Kwon and Østergaard[55] (Denmark), Henning and Palzer,[56] and

Nitsch et al.[57]]. Australia and Japan are a new focus of four analyses. While Elliston et al.[58] show that a 100% electricity supply for Australia is feasible, Trainer[59] comes to the conclusion that the investment costs for such system could be unaffordable—a claim that he reiterates in his criticism (Refs 60 and 61) of the work of Jacobson and Delucchi, which is rejected by Jacobson and Delucchi (Ref 62) and which does not seem to hold in the light of the cost estimates of other studies (e.g., Ref 14 or Ref 63). For Japan, Esteban et al.[64] show that a very substantial part of the electricity supply could be covered by renewable energy sources, but that storage may become a bottleneck for a 100% renewable electricity system. In the same year, Tsuchiya[65] publishes his analysis on the optimal mix of different renewable resources for a largely renewable electricity supply for Japan. In 2012, the most extensive analysis of the future prospects of the global energy supply, the Global Energy Assessment,[66] is published. One of its key findings is that 'The share of renewable energy in global primary energy could increase from the current 17% to between 30 to 75%, and in some regions exceed 90%, by 2050'. At the same time the most extensive analysis of the possible future renewable electricity supply for the United States, the Renewable Electricity Futures Study[63] is published by NREL, assessing a variety of scenarios with 30–90% of renewable electricity, with a focus on 80% (Ref 63, p. iii). The central conclusion of this extensive study is 'that renewable electricity generation from technologies that are commercially available today, in combination with a more flexible electric system, is more than adequate to supply 80% of the total US electricity generation in 2050 while meeting electricity demand on an hourly basis in every region of the United States' (Ref 63, p. iii).

Although this article can only include publications until late July 2013, this year has already seen nine further publications in the field of up to 100% renewable energy supply (Refs 67–70 and 72–74). Among these, we find three detailed studies on states of regions of the United States (Refs 69–70) and three studies on Australia (Refs 72–74), whereas the remaining two deal with Greece (Ref 67) and the UK (Ref 68). None of these studies raise serious doubts about the possible transition toward a largely renewables-based future energy supply.

In his publication 'The renewable energies technology surge: A new techno-economic paradigm in the making?', Matthews[75] puts forward the idea that the transition to a renewable world energy supply could mark the shift to the sixth techno-economic paradigm (as the sixth long K-wave according to Kondratiev; see Ref 75, p. 10). Thus, we might be looking at the most fundamental techno-economic trend of our time. Beyond this basic observation, one of his main conclusions is that 'the success of the shift to REs depends on dismantling the systemic supports for fossil fuel systems' (Ref 75, p. 10).

By now we know from numerous in-depth studies that it will be possible to supply most of the world energy demand and close to 100% of the world's electricity demand by renewable energy sources by the year 2050. If this can be realized, it will be the most important single contribution to the mitigation of human-induced climate change.

In the next chapter, the study of the German Council of Environmental Advisors is taken as a prototype example to show how a detailed state of the art analysis is undertaken in the electricity sector and which central questions remain to be addressed.

THE 100% RENEWABLE ELECTRICITY STUDY OF THE GERMAN COUNCIL OF ENVIRONMENTAL ADVISORS

The German Council of Environmental Advisors is an independent body of seven university professors appointed by the German government for a 4-year term of office. It is supported by a substantial budget granted by the German Bundestag and by a scientific and administrative staff of about 20 persons. The author has been a member of the council from 2008 to 2012, being responsible for the special report on 100% renewable electricity supply (Refs 14, 34, 43), which is the basis of this article.

The Methodology

The methodology used to analyze the possibilities of a 100% renewable electricity supply for Germany and Europe together with North Africa is an hourly simulation of the electricity system in 2050, based on the regional distribution of the potential of the different renewable energy sources and on the regional distribution of different storage options (pump storage, compressed air storage, and storage in the form of hydrogen). Based on the hourly simulation of wind and solar energy production, controllable production and storage units are dispatched. The system optimizes the production and storage for each hour of the year and derives a minimum cost solution for the annual electricity production.

All calculations for the study were performed by the systems analysis group of the German Aerospace Center [Deutsches Zentrum für Luft- und Raumfahrt (DLR)] in Stuttgart with the linear optimization model REMix-Europe. This model is based on an extensive

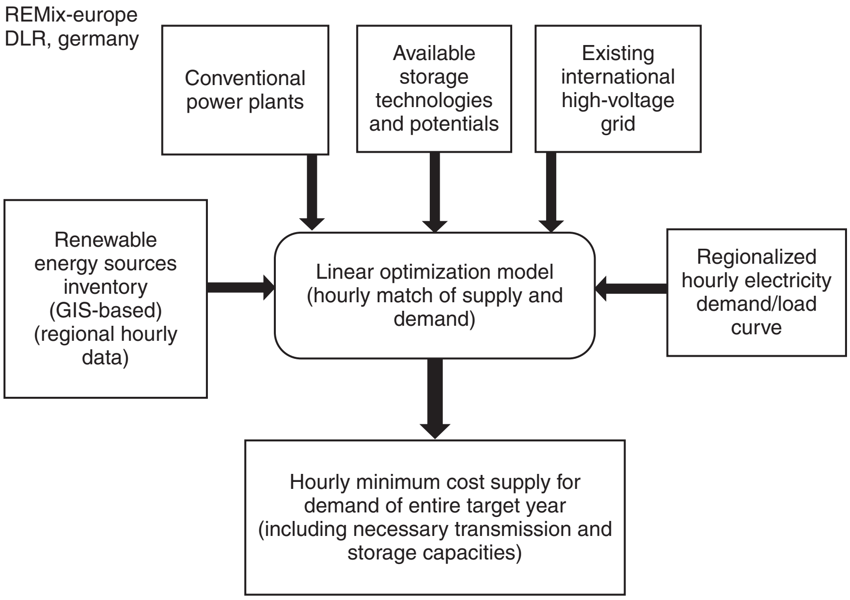

FIGURE 1 | Overview of the model structure of the techno-economic optimization model REMix-Europe of Deutsches Zentrum für Luft- und Raumfahrt (DLR) used for all calculations for the German Council of Environmental Advisors (SRU) analysis.

geographical information system (GIS), containing all relevant information on the spatial and temporal distribution of the renewable energy supply options and the electricity demand. Figure 1 gives an overview of the model structure of REMix-Europe. The model includes a detailed assessment of the hourly generation potential of the different renewables with a high special resolution. It combines this with a regionalized hourly load curve, which is to be met. The model optimizes the installed and operated capacities to minimize the electricity production costs of the target year 2050 under the condition of 100% renewable electricity production in the region considered in a given target scenario. The mathematical formulation of the target function and all other parts of the model can be found in the documentation of the model (Ref 76). The model does include the cost of the necessary international transmission and flags necessary transmission extensions. It calculates the necessary storage capacities and optimizes the use of storage from three given possible technologies (pump storage hydro, compressed air storage, and hydrogen storage). The documentation of the model can be found in DLR.[76] The chosen model uses just one of many possible modeling approaches, which are characterized quite well in an overview by Connolly et al.[77]

The major strength of the model is its capability to include the hourly production potential of the different renewable energy sources at a high level of spatial resolution and to derive a minimum cost solution for an integrated 100% renewable energy supply system. The central weakness of the approach is the concentration on electricity production. This does not allow to analyze the possible benefits of combining renewable electricity with heat generation and storage or with electrical cars. Thus, the analysis will need to be extended to a more comprehensive system perspective including heat and transportation energy demand as well. At the same time, one major weakness of the detailed modeling approach is the very extensive calculation time of up to 2 months for a scenario including the 36 countries of Europe and North Africa, which will make it very difficult to integrate heat and transportation energy demand into the analysis. Furthermore, the cost digression curves for the different renewable energy sources can be disputed. The most recent development has shown that the cost digression of solar PV was underestimated, whereas the cost digression of offshore wind energy was overestimated. It can be further argued that the assumed maximum installed capacity for onshore wind (about 40 GW) is far too conservative in view of an already installed capacity of about 30 GW and a target range of 33–70 GW of the national grid development plan 2012 (Netzentwicklungsplan) for the year 2022 (Ref 78, p. 6). Other studies have shown a maximum technical potential of about 720 GW for onshore wind in Germany (Ref 79). Nevertheless, the German Council of Environmental Advisors (SRU) study assumed the relatively low limit of 40 GW to onshore wind in order to not expose the results to the criticism that the utilization of a very high onshore wind potential would never be accepted by the general public. Another weakness of the chosen techno-economic modeling approach is the lack of ability to analyze important technical issues such as grid stability of the solutions calculated, as they are discussed in Lund.[80] Such issues need to be addressed

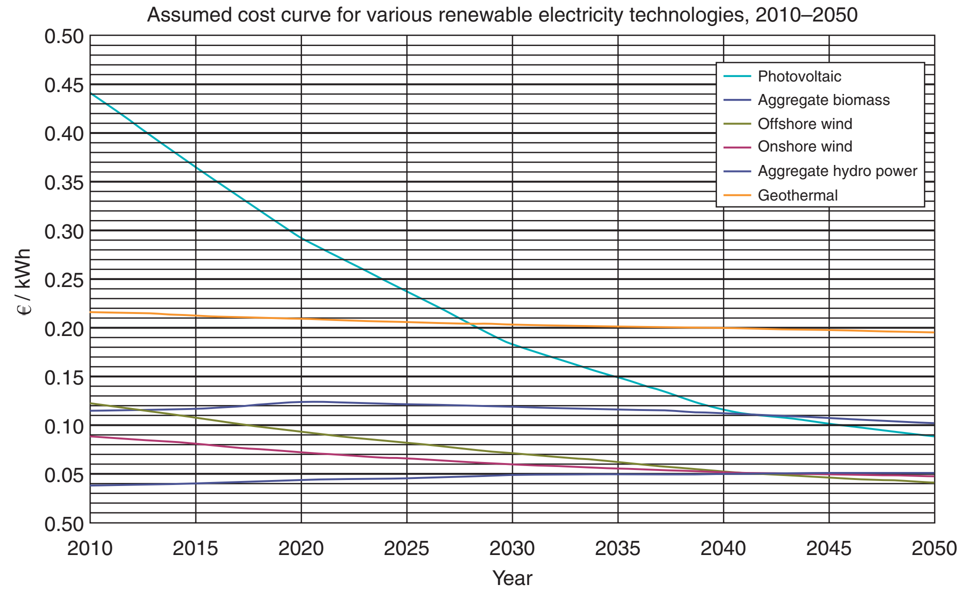

FIGURE 2 | Assumed cost development for the various renewable electricity generation technologies until 2050. (Reproduced with permission from Ref 14, p. 149. Copyright 2012, Sacherständlgenrat für Umweltfragen)

separately on the basis of the results calculated by REMix-Europe.

The costs for the different technologies were derived based on a learning cost curve approach and a database of the DLR[76] (p. 24). The assumed technology cost developments are shown in Figure 2 above. All cost figures are given in Euros of 2010. Future cost estimates are based on real costs of 2010. For concentrating solar power (CSP), it is assumed that the collector field has about three times the capacity of the turbine and that up to two thirds of the output can be stored in high temperature storage for nighttime operation (see Ref 76, p. 11). As costs are calculated on a site-specific basis, the assumptions concerning the future cost development of the technologies cannot be summed up in one figure. The full documentation of all assumptions concerning the future cost development can be found in detailed tables in Ref 76 (pp. 51–56).

The simulation was done for eight different scenarios, which cover a relatively wide range of possible future electricity demand (500–700 TWh/a for Germany and 5400–7200 TWh/a for the Europe plus North Africa). This range was estimated based on a large number of national and international studies of the future electricity demand (Ref 14, pp. 46 and 49). The assumed electricity demand of the target year 2050 does include a further substitution of natural gas through electricity in industrial processes and a shift of individual transport to electric cars. It does not include the additional electricity demand for a shift of truck transport to electricity as suggested in a later publication of the SRU (Ref 81, pp. 150–152).

The first two scenarios (1.a and 1.b) assume that Germany has no electrical connection to the outside world, needs to supply 500–700 TWh/a entirely from renewable sources in Germany, and has to store all electricity nationally to match demand in every hour of the year. Although this is a rather unrealistic assumption, it demonstrates that Germany can supply itself entirely with electricity from internal renewable energy resources, independent of any electricity import. At the same time, it shows the cost of such an attempt undertaken in full isolation. The next two scenarios (2.1.a and 2.1.b) relax the assumptions only with regard to storage. In these scenarios, connections with Denmark and Norway are allowed to store electricity with the help of the Norwegian hydropower system. Nevertheless, all electricity consumed in Germany has to be produced from renewable energy sources in Germany. In two more scenarios (2.2.a and 2.2.b), the restrictions are relaxed further to allow a net import of up to 15% of the annual electricity demand from the other two countries. Still, the countries covered are Germany, Denmark, and Norway, each country using only 100% electricity from renewable energy sources. In the last two scenarios (3.a and 3.b), the entire EU27 plus all eastern European countries up to the Russian border, Turkey, and the five North African countries directly adjacent to the Mediterranean Sea are included in the calculations. The acronym used for the area is EUNA. All countries are allowed to import

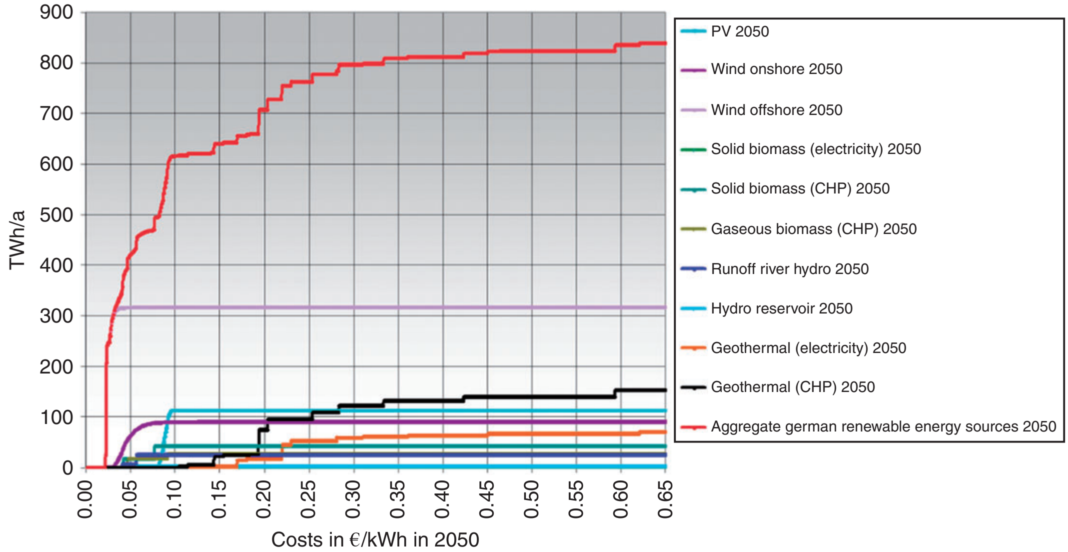

FIGURE 3 | Renewable electricity generation potential in Germany, in TWh/a as a function of per kWh costs. (Reproduced with permission from Ref 14, p. 72. Copyright 2012, Sacherständlgenrat für Umweltfragen)

up to 15% of their annual electricity demand from the other countries. All electricity used in the area has to be produced 100% from renewable energy sources.

For all scenarios, the necessary installed production and storage capacities as well as the necessary additional transmission capacities between all countries are included. For each scenario, the hourly and annual electricity production and the production costs are calculated. In case, a country is not able to supply at least 85% of its annual electricity consumption from its national renewable energy resources, the 85% restriction is lowered until the country can supply all its electricity demand from domestic and imported renewable energy sources.

Once the scenarios for 2050 were calculated, a transition pathway for the German electricity system was developed, starting from the present capital stock of conventional power plants and the installed production capacity from renewable energy sources. Such pathway was only constructed for scenario 2.1.a (500 TWh/a electricity demand in Germany, 100% production in Germany, storage possibilities in Norway can be used). The calculations were based on an average operational life time of conventional power plants of 35 years—a rather conservative assumption—and an average operational life time of wind, solar, and biomass-based systems of 20 years and an assumed life span of 50 years for large hydropower installations. The future annual demand for new generation, storage, and transmission capacity was calculated to meet the annual electricity demand and to develop into the target system resulting from the simulations for the year 2050. No sharp increases in production capacities for renewable energy technologies were assumed.

Once the pathway was developed, the investment and operation costs of the system could be calculated on a yearly basis. From these costs, the development of the cost of electricity was calculated per kWh. These were compared to two possible development pathways for electricity produced solely from conventional sources, covering a rather large range of possible future price developments (Ref 14, p. 153).

The Results for 2050

The Generation Potential

A detailed analysis of the potential of all relevant renewable energy sources in Germany shows that even under rather conservative assumptions there is a potential of about 835 TWh/a to supply all the forecast electricity demand for 2050 (500 or 700 TWh respectively) purely from German renewable energy sources as shown in Figure 3. Nevertheless, the scenario with the high demand gets close to the limits of the calculated resource potential and induces rather high costs for the last 100 TWh/a, as it needs to draw upon electricity produced from relatively low temperature geothermal heat. The results have met with some criticism, as rather low potentials for onshore wind energy (about 40 GW as maximum installed capacity) and for photovoltaic solar energy (about 100 GW as maximum capacity) have been calculated based on rather restrictive assumptions. There has been one analysis claiming a potential of over 720 GW of onshore wind energy (Ref 79,

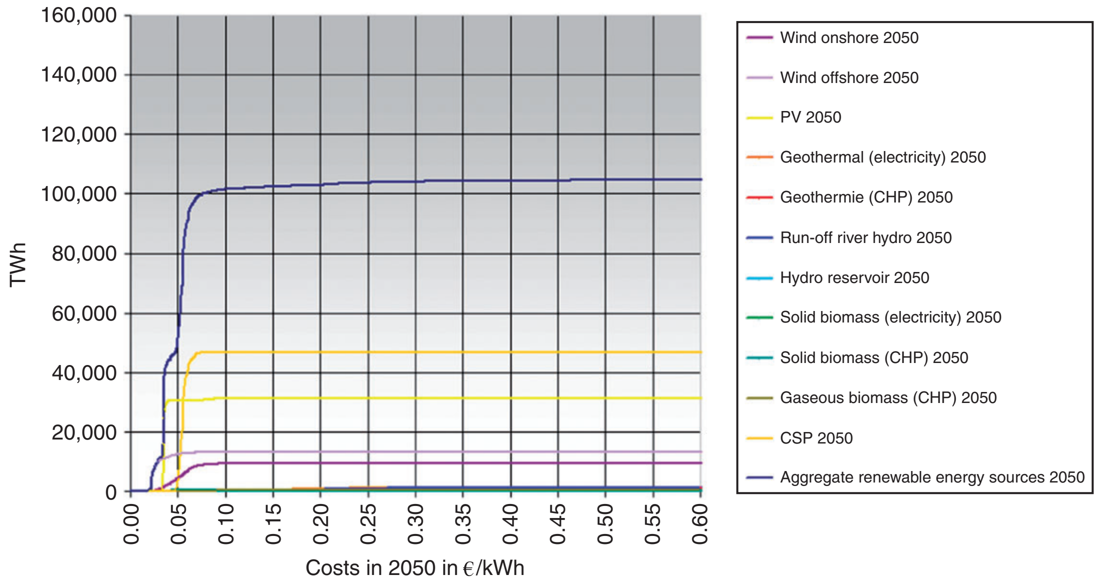

FIGURE 4 | Renewable electricity generation potential in Europe–North Africa, in TWh/a as a function of per kWh costs. (Reproduced with permission from Ref 14, p. 77. Copyright 2012, Sacherständlgenrat für Umweltfragen)

p. 17) in Germany, constituting many times larger total production potential.

The restrictive assumptions chosen by the SRU were based on considerations of public acceptance of onshore wind energy. If the real development will prove that public acceptance can be secured for the use of significantly larger land areas, the onshore wind energy potential can supply a very large part of the German electricity demand.

Considering the entire EUNA area (Europe and the five North African countries on the Mediterranean), the potential increases by more than factor 100 to 105,000 TWh/a, which can be generated from the different renewable energy sources, as shown in Figure 4. As the demand for the area is estimated to be just under 5400 TWh/a in scenario 3.a analogous to the 500 TWh/a scenario for Germany, this is about 20 times the necessary electricity production.

Results for Germany 2050

The scenarios for 2050 show that it is possible to supply Germany with 100% electricity from internal renewable energy sources every single hour of the year (Table 1). Although this is possible, the attempt is faced with a serious shortage of cheap seasonal storage. Thus, about 300% of the maximum grid load of about 81 GW (in scenario 1.a), a total of 262 GW of installed capacity in renewable power generation or storage, is required to meet the total demand. In scenario 1.b (700 TWh/a), a maximum load of 112 GW is met by an installed capacity of 321 GW. Details can be seen in Table 2.

The lack of cheap long-term storage in Germany can be seen from Figures 5 and 6, as very large quantities of possible electricity production cannot be used or stored. In order to meet the demand in every hour of the year, it is necessary to install the huge overcapacities, which can generate far more than the required power, if the wind blows well on a sunny day. In an extreme case, in the month of May (Figure 6) a possible power generation of about 140 GW is faced with a demand of just under 50 GW, leaving a possible production of 90 GW unused. As the limited compressed air storage is already filled up and the model does not include the use of such possible overproduction of electricity for other uses such as heat, the possible excess production is curtailed and no possible economic benefits of such uses are taken into account.

Interestingly enough, the optimization program did not choose to use hydrogen storage in any single hour of the year in spite of the large unused production potential. Thus, the investment in larger overcapacities was still the cheaper option as compared to hydrogen storage.

Only a relatively small capacity of pump storage was allowed to be used for general storage purposes, as most of the available capacity was reserved for system services such as voltage and frequency stabilization. Additionally, no new pump storage capacity was assumed to be built in Germany. Even if these assumptions would have been changed, the existing pump storage plants could only supply relatively small storage volumes. Presently, the system has a generation

TABLE 1 | Specifications of the Eight Scenarios Analyzed for a 100% Electricity Supply from Renewable Energy Sources (The demand given in the first row is the electricity demand in Germany) (Reproduced with permission from Ref 14, p. 69. Copyright 2012, Sacherständlgenrat für Umweltfragen)

Scenario group	Characterization	Demand in 2050: 500 TWh/a	Demand in 2050: 700 TWh/a
1	Complete self-sufficiency in Germany	Scenario 1.a DE 100% SV-500	Scenario 1.b DE 100% SV-700
2	Complete self-sufficiency in Germany in terms of annual production Interchanging of up to 15% of annual output with Denmark and Norway	Scenario 2.1.a DE–DK–NO 100% SV-500	Scenario 2.1.b DE–DK–NO 100% SV-700
	Up to 15% net import of electricity from Denmark and Norway (plus interchanging of up to 15% of annual output)	Scenario 2.2.a DE–DK–NO 85% SV-500	Scenario 2.2.b DE–DK–NO 85% SV-700
3	Up to 15% net import from Europe–North Africa (EUNA) allowed (plus interchanging of up to 15% of annual output)	Scenario 3.a DE–EUNA 85% SV-500	Scenario 3.b DE–EUNA 85% SV-700

TABLE 2 | Installed Capacities, Annual Power Production, Annual and Specific Power Costs in Scenarios 1.a and 1.b (Reproduced with permission from Ref 14, p. 86. Copyright 2012, Sacherständlgenrat für Umweltfragen)

Energy source/technology used for scenario	Capacity used		Electricity produced		Costs			
	Maximum GW		TWh/a		Millions of Euros per year		Euro-cents per kWh	
	1.a	1.b	1.a	1.b	1.a	1.b	1.a	1.b
Photovoltaics	85.9	109.6	87.9	112.2	7798	9957	8.9	8.9
Solar thermal								
Onshore wind	33.1	39.5	76.0	90.6	3578	4267	4.7	4.7
Offshore wind	73.2	73.2	316.9	316.9	13,056	13,057	4.1	4.1
Geothermal								
Geothermal with CHP	0.0	18.3	0.0	147.1	0	29,696	0.0	20.2
Solid biomass	26.8	30.8	44.5	44.5	11,664	12,734	26.2	28.6
Solid biomass with CHP	0.0		0.0					
Biogas	0.0		0.0					
Biogas with CHP	6.6	6.7	26.6	26.6	4687	4745	17.6	17.8
Run-of-river hydro	4.1	4.1	25.3	25.3	1337	1337	5.3	5.3
Hydro reservoir storage	0.4	0.4	2.3	2.3	119	119	5.3	5.3
Totals/average (gross)	230	283	579.5	766	42,239	75,911	7.3	9.9
Electricity imports	0	0	0.0	0	0			
Electricity exports	0	0	0.0	0	0			
Electricity storage								
Pump storage (storage)	0.5	0.6	1.2	1.4				
Pump storage (generation)	0.5	0.6	1.0	1.1	68	85	7.1	7.7
Compressed air (storage)	32	37	50.5	60.3				
Compressed air (generation)	32	37	33.5	39.7	3654	4660	10.9	11.7
Hydrogen (storage)	0	0.0	0.0	0.0				
Hydrogen (generation)	0	0.0	0.0	0.0				
Storage loss			17.2	21				
Total demand/costs	81	112	509.0	700	45,960	80,656	9.0	11.5
Surplus capacity/production	181	209	53.3	45				

CHP, combined heat and power production

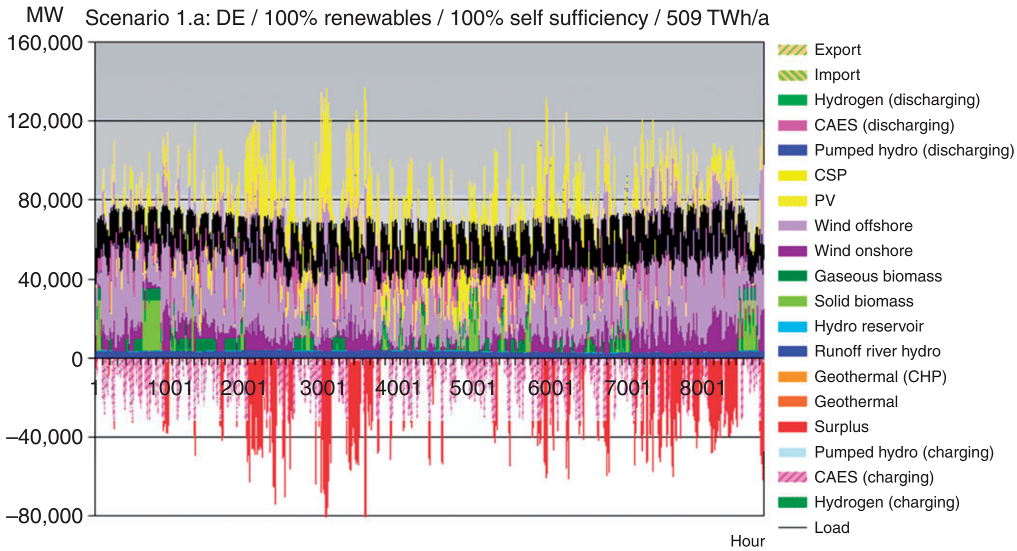

FIGURE 5 | Hourly production meets hourly demand in Germany in 2050 in scenario 1.a. Negative values are either stored or overproduced electricity. (Reproduced with permission from Ref 14, p. 85. Copyright 2012, Sacherständlgenrat für Umweltfragen)

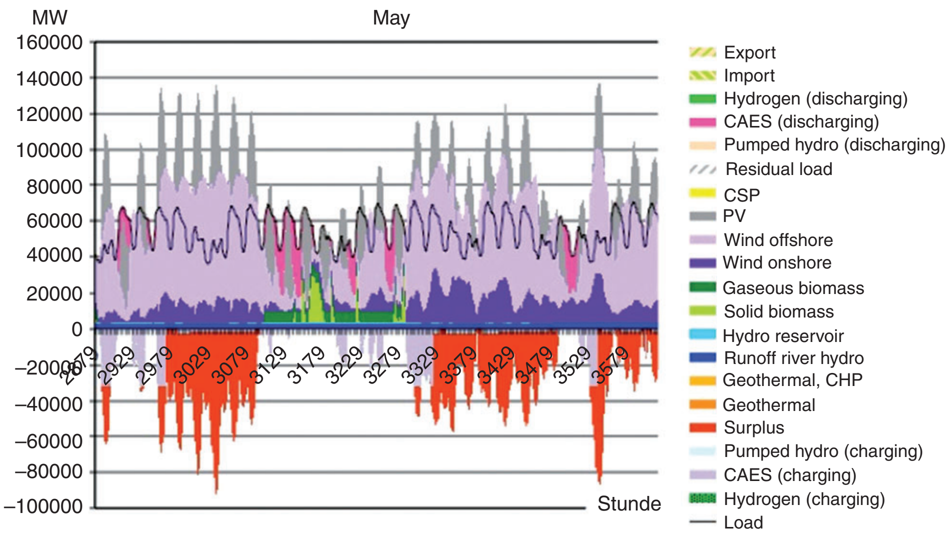

FIGURE 6 | The lack of adequate storage in Germany is especially evident in May 2050 in scenario 1.a [calculations done for Ref 14 by Deutsches Zentrum für Luft- und Raumfahrt (DLR)]. (Reproduced with permission from Ref 14. Copyright 2012, Sacherständlgenrat für Umweltfragen)

capacity of about 7 GW from pump storage plants, which access just about 40 GWh of storage (Ref 82, p. 8). Thus, under full capacity these plants can only supply power for 6 h. New pump storage plants would have a similar ratio of generation capacity to storage volume restricting these storage facilities to daily storage cycles such as the planned facility at Atdorf in Baden-Wuertemberg (Ref 83, p. 13).

The installed overcapacities led to a nonutilized production potential of about 53 TWh/a in scenario 1.a and 45 TWh/a in scenario 1.b. The lack of low cost long-term storage in Germany leads to overall electricity costs of about 9 c€/kWh in the 500 TWh/a scenario (1.a) and to about 11 c€/kWh in the 700 TWh/a scenario. The 2 c€/kWh difference between the two scenarios mainly results from the fact that the high demand scenario needs to additionally draw on the rather expensive potential of geothermal electricity generation in Germany, which is not used for the moderate demand scenario.

The Impact of Norwegian storage

In the next four scenarios (2.1.a, 2.1.b, 2.2.a, and 2.2.b) the analysis was not limited to Germany any more. In the 2.1.a and 2.1.b scenarios electricity export for storage was allowed through Denmark to

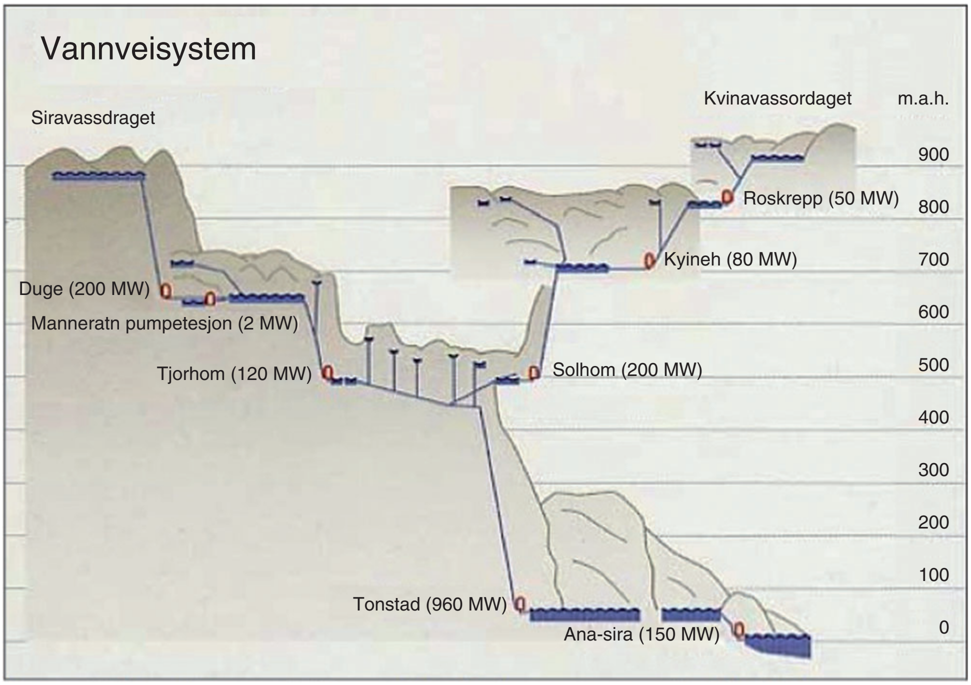

FIGURE 7 | Sketch of the Norwegian hydropower system Sira-Kvina. (Source: Ref 85, p. 8)

Norway. Norway plays an important role in these considerations, as it has a huge hydropower system with a storage capacity of 84,300 GWh (Ref 84), which is about 2200 times the volume of all German pump storage reservoirs. A major part of this system can be changed into an extremely large pump storage system just by adding generation, pumping, and tunnel capacity between different existing storage lakes. An almost unique feature of the Norwegian hydropower system is the fact that often a number of large storage lakes on three to four different levels are connected in one hydropower scheme like in the hydropower system Sira-Kvina, which is sketched in Figure 7.

Presently, there is very little pumping capacity as the hydropower storage system contributes about 95% (94.7% in the rather bad hydropower year 2010) of Norway's electricity production (Ref 86). For the scenarios, it was assumed that Norway can actually convert a major share of its storage capacity to pump storage. In the scenarios, it was further assumed that all three countries produce 100% of their electricity from renewable energy sources. The hourly optimization was done similar to the scenarios 1.a and 1.b.

The overproduction of renewable electricity is reduced to <0.2 TWh/a in scenario 2.1.a requiring only a very minor adjustment of the operation of wind power generation in Germany. As Figure 8 shows, practically all temporary overproduction can be stored with the help of the Norwegian hydropower system. Only during about 15 h of the year some overproduction exists, which is not stored, as the investment for additional pumps and power lines is too expensive.

As can be seen from Table 3 the expansion of the system to the three countries, just allowing the electricity exchange for storage, leads to a decrease in installed generation and internal storage capacity in Germany to 182 GW in scenario 2.1.a (German demand of 500 TWh/a) and 271 GW in scenario 2.1.b (700 TWh/a). In scenario 2.1.a, the installed capacity in Germany is cut to <70% of the capacity installed in the case of the 'splendid isolation' of scenario 1.a (262 GW). At the same time, a Norwegian pump storage capacity of about 42 GW is used for a part of the short-term and all of long-term German storage.

The electricity costs including storage, losses, and transportation costs drop to about 7.0 c€/kWh in scenario 2.1.a and to 9.8 c€/kWh in scenario 2.1.b. Thus, a cooperation with Norway leads to a cost reduction of about 10 billion €/a for the supply of a 100% renewable energy in Germany.

In scenarios 2.2.a and 2.2.b, the restriction of a 100% national renewable electricity production is relaxed to make the scenarios more realistic, as export and import of electricity are the general practice in Europe. To assure that the system does not become dependent on a large share of imported renewable electricity, the net imports were restricted to 15% of the national electricity demand.

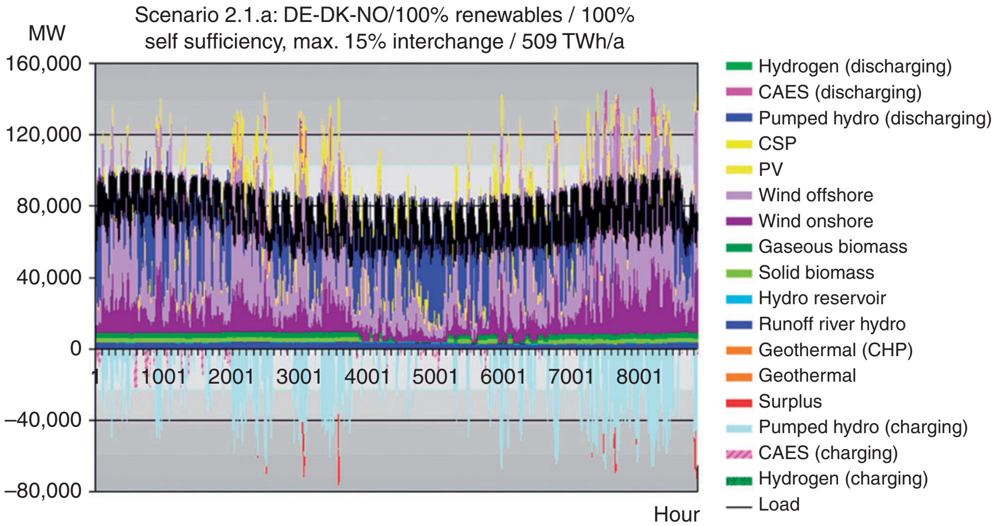

FIGURE 8 | Hourly production meets hourly demand in Germany, Denmark, and Norway in scenario 2.1.a. Negative values are either stored or overproduced electricity. (Reproduced with permission from Ref 14, p. 90. Copyright 2012, Sacherständlgenrat für Umweltfragen)

The installed power generation and storage capacities in Germany drop further to 126 GW in scenario 2.2.a and 258 GW in scenario 2.2.b. The production matches demand very well like in the 2.1 scenarios. The required Norwegian storage does not increase but the imports from Norway and Denmark increase to the allowed 15%. At the same time, the costs drop by 0.5 c/kWh to 6.5 c€/kWh in scenario 2.2.a, equivalent to 2.5 billion €/a and by 2.6 c/kWh to 7.2 c/kWh in scenario 2.2.b., equivalent to more than 18 billion €/a.

It can be concluded that up to 500 TWh/a the German renewable electricity generation potential has only slightly higher costs than the production in Denmark or Norway, but the last 100 TWh/a in the case of the 700 TWh/a in scenario 2.2.a have significantly higher costs than the import of this quantity from Denmark or Norway, allowing for the substantial cost reduction by net imports—a fact that could be guessed from the structure of the German renewable cost in Figure 3.

Results for Europe Plus North Africa (EUNA)

In scenario 3.a the 43 countries of the region of Europe to the Russian border plus the five North African countries directly adjacent to the Mediterranean Sea have been considered. As some smaller countries are grouped together, only 36 single countries or country groups are shown in the figures below. Again, it is assumed that the entire area has to supply itself by 100% renewable electricity. Each country has to produce at least 85% of its electricity from internal renewable energy sources and the exchange of electricity for storage purposes is allowed. Analogous to the 500 TWh/a demand scenarios for Germany, the region is estimated to have an electricity demand of just under 5400 TWh/a in 2050 (Ref 10, p. 99). The maximum load in the system is assumed to be about 840 GW. To meet this demand in every hour of the year, an overall capacity of about 1700 GW of production capacity including about 100 GW of pump storage hydro and about 240 GW of compressed air storage is used.

Wind power generates about 63% (3400 TWh/a) of the electricity, whereas CSP generates about 1080 TWh/a, and photovoltaic solar energy (PV) generates about 575 TWh/a (Ref 14, p. 99). Although the solar potential is far larger than the potential of wind energy in the area, wind is the main contributor because of its lower cost. The contribution of the installed 230 GW of compressed air storage is about 190 TWh/a, which is similar to the 180 TWh/a of electricity production from pump hydro storage with an installed capacity of about 100 GW (Ref 14, p. 99).

Considering that wind energy is the energy supply option mainly used, it is no surprise that the wind-rich countries Norway, Ireland, UK, and Denmark are the main exporters of electricity, as shown in Figure 9. Nevertheless, the fact that all North African countries included in the analysis are net importers of electricity in the scenarios does not meet the standard expectation that North Africa will be the solar power house for Europe in the future, which could supply 15% of Europe's electricity demand (see e.g., Ref 87).

Only 2 of 43 countries in the area are not able to supply at least 85% of their national electricity demand from internal renewable energy sources.

TABLE 3 | Installed capacities, annual power production, annual and specific power costs in scenarios 2.1.a and 2.1.b (Reproduced with permission from Ref 14, p. 89. Copyright 2012, Sacherständlgenrat für Umweltfragen)

Energy source/technology used for scenario	Capacity used		Electricity produced		Costs			
	Maximum GW		TWh/a		Millions of Euros per year		Euro-cents per kWh	
	2.1.a	2.1.b	2.1.a	2.1.b	2.1.a	2.1.b	2.1.a	2.1.b
Photovoltaics	40.9	109.6	41.9	112.2	3714	9957	8.9	8.9
Solar thermal		0.0		0.0		0		
Onshore wind	39.5	39.5	90.6	90.6	4267	4267	4.7	4.7
Offshore wind	73.2	73.2	316.9	316.9	13.057	13.057	4.1	4.1
Geothermal		0.0		0.0		0		
Geothermal with CHP		14.4		119.8		23.314		19.5
Solid biomass		0.0		0.0		0		
Solid biomass with CHP	2.5	3.0	17.1	17.1	1983	2.249	11.6	13.2
Biogas		0.0		0.0		0		
Biogas with CHP	2.4	2.9	17.1	17.1	1495	1741	8.7	10.2
Run-of-river hydro	4.1	4.1	25.3	25.3	1337	1337	5.3	5.3
Hydro reservoir	0.3	0.3	2.3	2.3	92	92	4.0	4.0
Totals/average (gross)	162.9	247.0	511.2	701.3	25.944	56.013	5.1	8.0
Electricity reimporting	0.0	0.0	76.4	103.1	8.406	11.304	11.0	11.0
Electricity storage								
Pump storage (storage)	1.2	1.2	1.0	0.8				
Pump storage (generation)	1.2	1.2	0.8	0.6	171	170	21.4	28.3
Compressed air (storage)	18.1	23.5	5.7	4.0				
Compressed air (generation)	18.1	23.5	4.3	3.0	1189	1466	27.6	48.9
Hydrogen (storage)	0.0	0.0	0.0	0.0				
Hydrogen (generation)	0.0	0.0	0.0	0.0				
Storage loss			1.6	1.2				
Total demand/costs	81	111	509.4	700.1	35.709	68.953	7.0	9.8
Surplus capacity/production	101.2	160.7	0.2	0.0				

These are Belgium, which meets 67% of its demand, and Luxembourg, covering only 33% of its annual electricity demand from internal sources. Both countries display a rather unfortunate ratio of electricity demand to internally available renewable energy sources.

The electricity costs vary substantially between the different countries, as shown in Figure 10. The wind-rich countries show electricity costs as low as 4 c€/kWh, whereas countries with high shares of geothermal electricity have costs as high as 11.5 c€/kWh as in the case of Slovakia. While most countries have electricity costs below 7 c€/kWh, these figures compare to mean electricity prices of about 4.5 c€/kWh (45 €/MWh) at the European spot markets in 2010 (Ref 88, p. 7) or industry prices in EU27 of 10.5 c€/MWh (excluding VAT) or consumer electricity prices of 17.3 c€/kWh (including VAT) in 2010 (Ref 89). Belgium and Luxemburg have comparatively modest costs of about 6 c€/kWh (Belgium) and about 7.5 c€/kWh (Luxemburg) due to the higher import shares in spite of the forced utilization of their entire renewable resources. This indicates that a relaxation of the 15% restriction on net imports would certainly lead to drastic cost reductions in the countries with the worst resource base.

In the case of Germany, electricity costs decreased in the EUNA scenario 3.a to 5 c€/kWh as compared to 6.5 c€/kWh in scenario 2.2.a—a further cost reduction by about 7.5 billion €/a.

The German Pathway from 2010 to 2050

The analysis clearly shows that an electricity supply for Germany as well as for Europe and North Africa

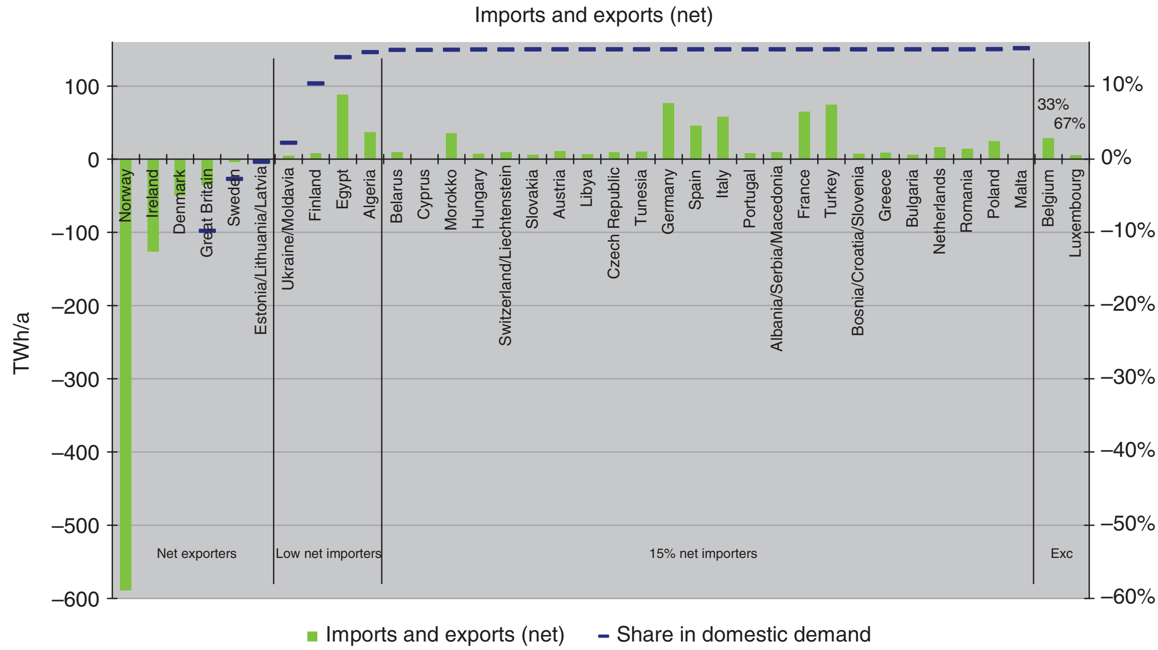

FIGURE 9 | Imports and exports of electricity in scenario 3.a in TWh/a and in per cent of the national demand. (Reproduced with permission from Ref 14, p. 429. Copyright 2012, Sacherständlgenrat für Umweltfragen)

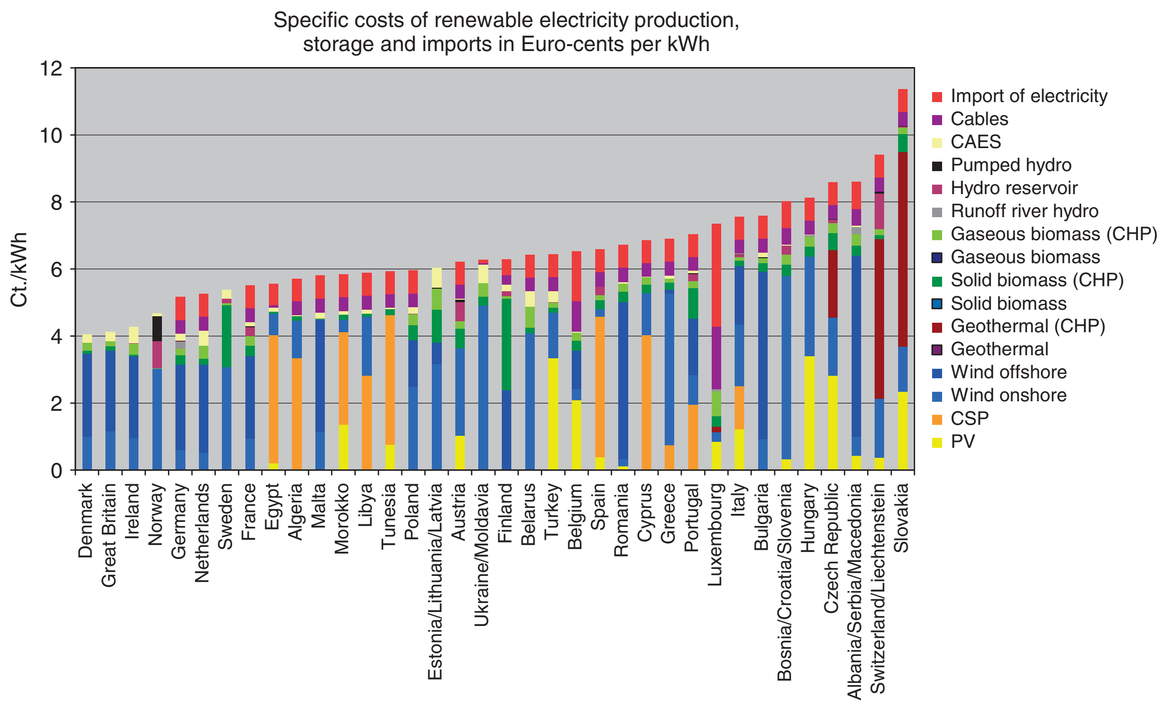

FIGURE 10 | Specific costs of renewable electricity production in scenario 3.a including production, storage, and transmission costs. (Reproduced with permission from Ref 14, p. 428. Copyright 2012, Sacherständlgenrat für Umweltfragen)

is feasible and the costs of such a system will be reasonable in 2050. Nevertheless, the question remains, how the transition from the present electricity system to a system based 100% on renewable energy sources can be achieved? This question was analyzed in the case of Germany, based on scenario 2.1.a. (Germany exchanging electricity with Norway for storage purposes). In the German public debate on the necessary transition ('Energiewende') away from fossil fuels and nuclear power toward renewable energy sources, the

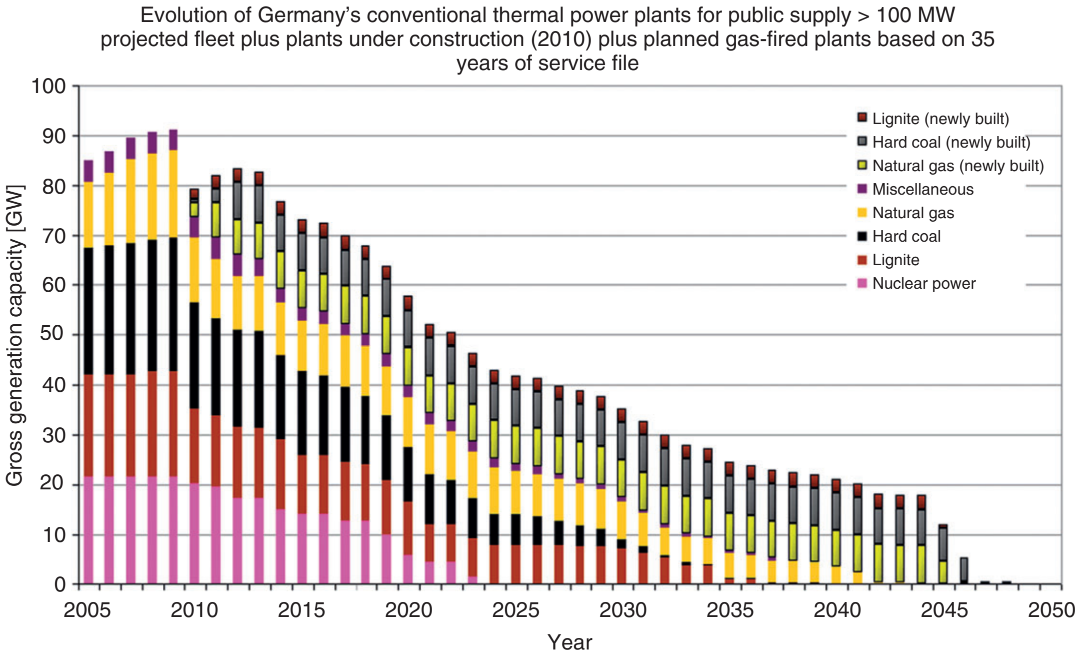

FIGURE 11 | Assumed evolution of Germany's conventional thermal power plant fleet including power plants under construction and gas-fired power plants in advanced planning in early 2010 assuming a 35-year life span for all power plants. (Reproduced with permission from Ref 14, p. 106. Copyright 2012, Sacherständlgenrat für Umweltfragen)

question of the necessary next steps toward the goal is a key issue of the debate. Will the shutdown of nuclear power plants until 2022 necessitate the construction of new coal or gas-fired power plants? Will we need new coal-fired power plants with CCS as an intermediate step or can a transition be achieved directly without any new conventional capacity?

To analyze these questions, the age structure of the German power plants was taken and it was assumed that each conventional power plant will need to be replaced by new generation capacity after 35 years of operation. This is a rather conservative assumption, as power plants are often operated between 35 and 50 years (see e.g., Ref 90, p. 9; Ref 91, p. 40; or Ref 92, p. 4). This assumption leads to the so called death row (Sterbelinie) of the national power plant stock as can be seen in Figure 11, which includes power plants under construction and gas-fired power plants in an advanced planning stage at the time of the analysis as early as 2010. The sharp drop of capacity in 2010 results from the use of historic data up to 2009 and the transition to the scenario assumptions (35 years operational life) in 2010. Thus, in the scenario all power plants older than 35 years are taken out of operation in 2010.

Assuming normal operation conditions for all power plants considered, this stock of power plants leads to a decreasing annual production potential, which is shown in the lower part of Figure 12. The upper part of the graph shows the gap between the assumed slowly decreasing electricity demand (according to scenario 2.1.a) and this conventional generation potential. It was analyzed whether this gap can be filled by renewable energy sources and storage without sudden large increases in the production capacity of technologies for the utilization of renewable energy sources.

It could be shown that the necessary installation of energy systems based on renewable energy sources in Germany does not necessitate an unlikely expansion of production and installation capacities as can be seen from Figure 13. The figure shows the historic development of renewable electricity generation capacities up to 2009 as well as the necessary future expansion to meet the annual electricity demand without building new conventional power plants after 2015. What is more, the necessary expansion of renewable power generation capacity slows down after 2023.

This slowdown is due to the assumed operational life span of 35 years for the conventional power plants constructed up to 2015. To allow for the normal operation of these plants, the development of the renewable power generation needs to slow down after 2023. If an earlier replacement of all conventional power plants would be allowed, a 100% renewable electricity supply would be possible by 2030, just by keeping the pace of installing renewables-based production capacity from 2010 to 2020.

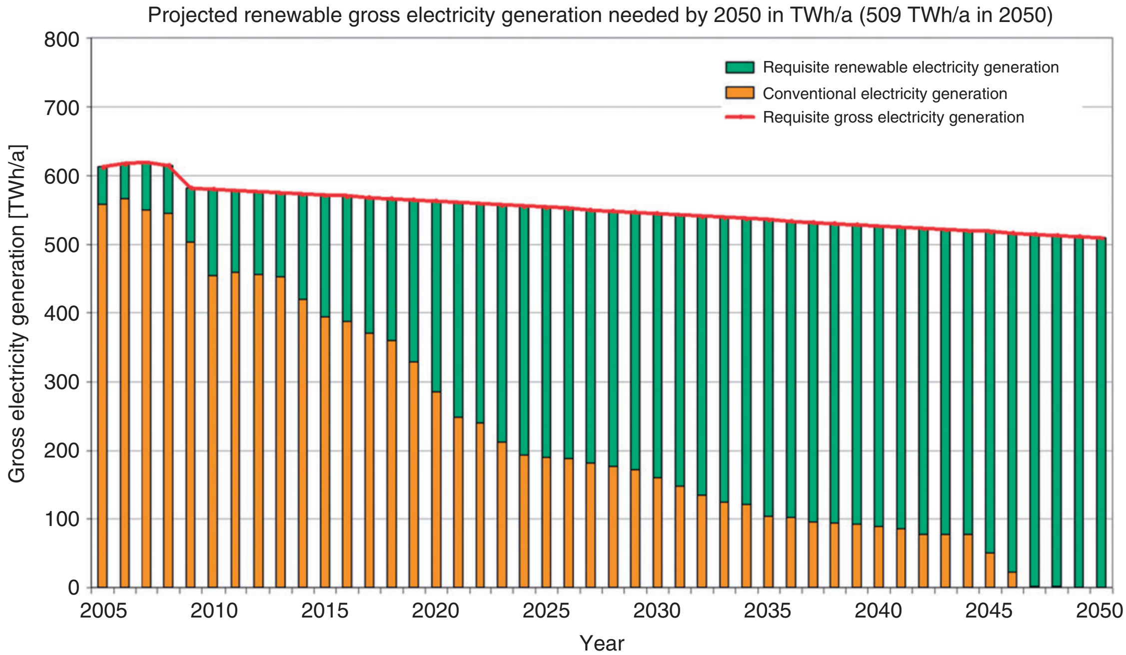

FIGURE 12 | Gap between electricity demand and remaining conventional power generation potential. (Reproduced with permission from Ref 14, p. 111. Copyright 2012, Sacherständlgenrat für Umweltfragen)

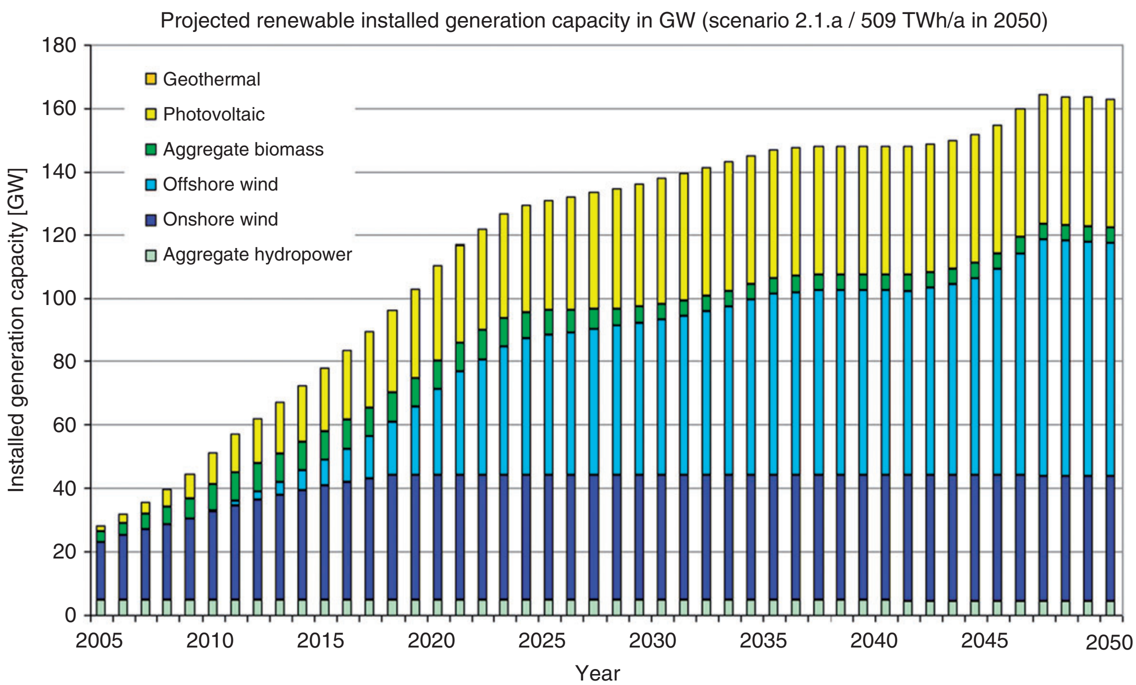

FIGURE 13 | The necessary expansion pathway of the renewable power generation capacities in Germany to close the demand gap based on scenario 2.1.a. (Reproduced with permission from Ref 14, p. 117. Copyright 2012, Sacherständlgenrat für Umweltfragen)

Thus, it could not be shown that a transition to a 100% renewable energy-based electricity supply by 2050 does not necessitate the construction of any additional new conventional power plants beyond the coal- and gas-fired power plants under construction and the gas-fired power plants in advanced planning stages by early 2010. It could even be demonstrated that such a transition can be achieved as early as 2030, if the latest conventional power plants are taken out of operation without being operated for 35 years. The

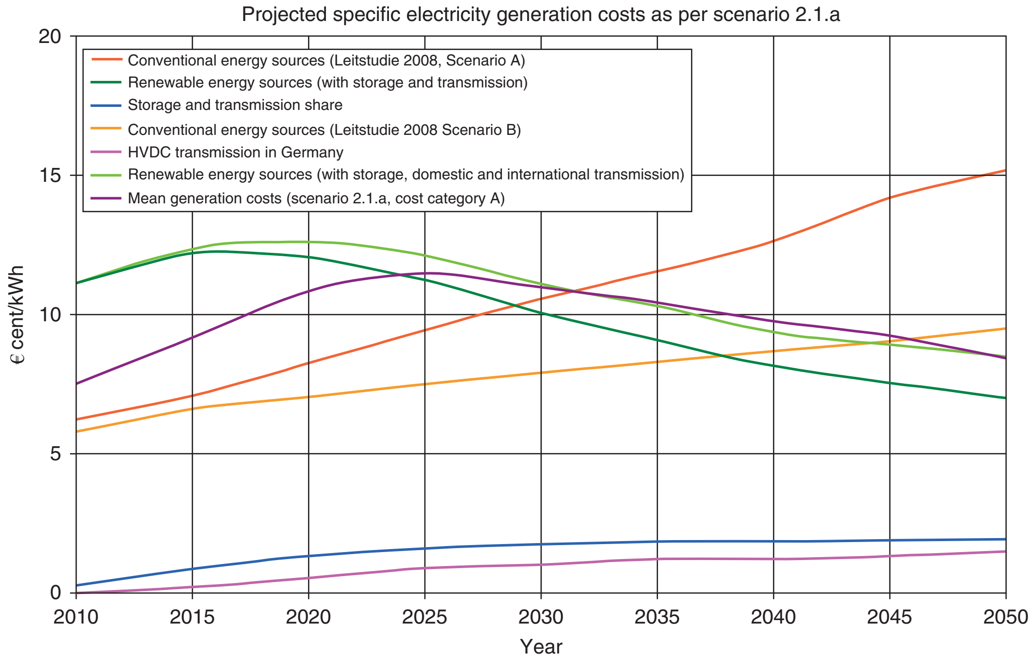

FIGURE 14 | The development of future conventional and renewable energy-based electricity production cost including storage and international and national transmission costs (based on scenario 2.1.a). (Reproduced with permission from Ref 14, p. 153. Copyright 2012, Sacherständlgenrat für Umweltfragen)

bottleneck for such a fast track development would certainly be the commissioning and construction of the necessary additional high-voltage power lines within Germany as well as the connection to and the conversion of the Norwegian hydropower system.

The Electricity Cost during the Transition

Even if a technical transition to a 100% renewable energy-based power system is possible, the question remains, whether such a transition will be affordable for the average electricity customer.

As the assumed transition will take until the year 2050, the cost of the new system has to be compared to the future costs of conventional electricity generation, which will not remain at its present cost level as fuel prices will most likely increase at least moderately. The SRU has adopted two cost development pathways for conventional electricity generation in Germany, a moderate and a considerable price increase, which were developed for the German government (Ref 93). The two assumed development pathways for conventional electricity are depicted in Figure 14 together with the development of the full costs of the renewable energy-based power generation including storage and the necessary expansion of national and international transmission capacities.

Conventional power costs grow from between 5 and 6 c€/kWh in 2010 to 9.5 and 15 c€/kWh in 2050 in constant prices with moderate or considerable cost increases. At the same time, the full production cost of electricity based on renewable energy sources including all storage and transmission costs increases from about 11.5 c€/kWh in 2010 to a maximum of about 13 c€/kWh in 2020, declining thereafter to 8.5 c€/kWh in 2050. The 2050 costs are about 1.5 c€/kWh higher than the figures given in Table 3. The latter do not include the costs for the expansion of the internal high-voltage grid in Germany, which were estimated separately by the SRU (Ref 14, p. 154) to be about 1.5 c€/kWh in 2050 in scenario 2.1.a. Depending on the future cost development of conventional power production renewable energy-based electricity will be the cheaper option for Germany after 2032, in the case of a considerable cost increase of conventional power, or after 2045, in the case of a moderate cost increase for conventional power generation. In any case, the electricity system based 100% purely on German renewable energy sources will be the lowest cost, long-term option for Germany, with even lower electricity costs if net imports are allowed.

As the costs of the transition system depicted in Figures 11–13 is a mixture of the cost of the shares of conventional and renewable energy-based generation costs, which change every year, the additional costs for the final consumer can be derived by the comparison of the weighted annual cost shares of the different generation technologies for the transition scenario

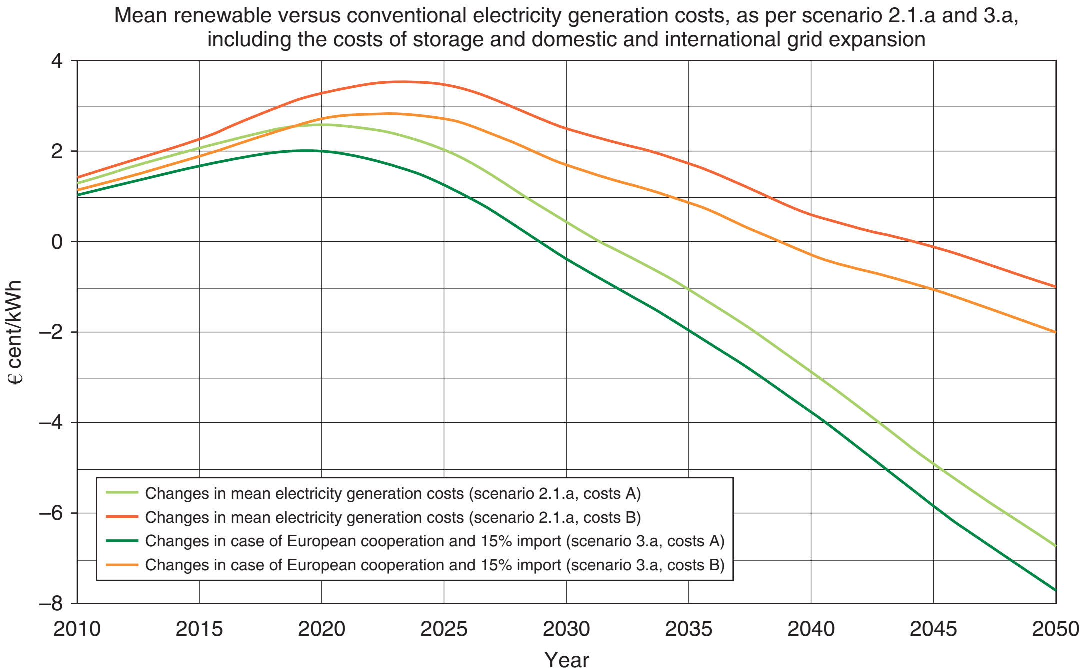

FIGURE 15 | Comparison of the electricity costs of the sketched transition system to 100% renewable energy-based power supply to a considerable and a moderate development of future conventional electricity production costs (based on scenario 2.1.a). (Reproduced with permission from Ref 14, p. 155. Copyright 2012, Sacherständlgenrat für Umweltfragen)

with the two assumed cost development pathways of a pure conventional electricity generation, which constitutes the present lowest cost option.

In Figure 15, only the difference between the conventional generation costs and the costs of the transition pathway are plotted. The lower curve gives the difference to the conventional high power cost development pathway (considerable cost increase), whereas the upper curve depicts the difference to the moderate conventional power cost development.

In the worst case (moderate conventional power cost development) for the transition cost comparison, the maximum additional costs are about 3.5 c€/kWh in year 2023. Even under these circumstances, the transition results in lower power costs from 2045 onwards. In the case of the considerable conventional power cost development pathway, the maximum additional costs of the transition are reached at 2.6 c€/kWh in 2020, with the start of very substantial cost savings in 2032, reaching a cost reduction of more than 6 c€/kWh by 2050 compared to future conventional electricity costs, which would translate into a reduction of 30 billion €/a of the German electricity cost in 2050. Thus, the transition to a 100% renewable energy-based electricity production will not only eliminate the large contribution of the German power sector to the emission of green house gases and the risk of nuclear power reactor accidents in Germany, it will even be the lowest cost, long-term electricity supply option judged on internal costs only.

CONCLUSION

Since the last 40 years, the vision of a 100% renewable energy supply and specifically a 100% renewable electricity supply for most countries of the world has become a serious option, which can become reality any time between 2030 and 2050 in many industrialized countries. Specifically, in Europe this option has moved into the public debate and we can see a paradigm shift in the official energy policy of countries such as Denmark and Germany and the energy policy of the EU Commission.

A power system based 100% on renewable energy sources will require very substantial capacities of short- and long-term storage to balance the system during times of low generation from wind and solar sources and to make use of the overproduction from these sources during times of very good production conditions. Pump storage hydropower will be in great demand for long-term storage.

A 100% renewable electricity system will need very substantial extensions of the national and international high-voltage grid infrastructure, as the centers of renewable energy production are often far from the centers of demand.

In the case of Germany, it could be shown that a transition from the present electricity supply system to a 100% renewable energy based system can be achieved without building any new conventional power plant beyond the coal-fired plants under construction and the gas-fired power plants in final planning stages in 2010. This holds even if an operational life of just 35 years is assumed for all conventional power plants, which is well below the industry practice.

A 100% renewable electricity supply could be the single most important contribution to the mitigation of man-made climate change. Nevertheless, the perspective taken in this article needs to be extended to a 100% renewable energy supply covering heat and transportation demand as well to solve the entire problem of global CO_2 emissions from energy conversion processes.

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