DIW Weekly Report

29+30 2021

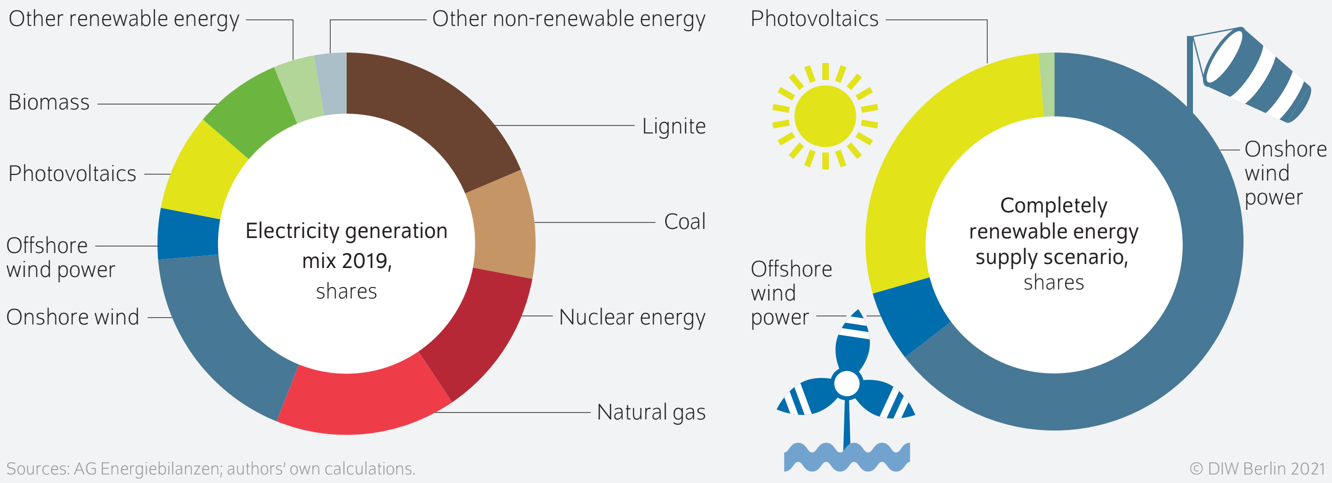
AT A GLANCE

100% renewable energy for Germany: coordinated expansion planning needed

By Leonard Göke, Claudia Kemfert, Mario Kendziorski, and Christian von Hirschhausen

- Completely renewable energy supply in Germany is possible and reasonable to reach the climate change targets
- Sufficient potentials in 38 planning regions and thus all German states
- Necessary to coordinate expansion planning for power generation, storage, and infrastructure
- Integration into the European electricity grid is important for supply security, which would be guaranteed in a 100 percent renewable energy system
- Prospect of a completely renewable energy system needs to be included in planning the overall energy system, both in Germany and in Europe

A fully renewable energy supply in Germany is possible but requires a fundamentally different electricity generation mix – onshore wind power would play the largest role



Sources: AG Energiebilanzen; authors' own calculations.

FROM THE AUTHORS

"We must greatly increase the pace of expansion, both for wind and solar energy. To achieve a completely renewable energy supply, we need to create the framework conditions for all sectors—not only for electricity, but for heating and mobility too. Then it could happen very quickly."
— ***Claudia Kemfert*** —

MEDIA

Audio Interview with Claudia Kemfert (in German)
www.diw.de/mediathek

100% renewable energy for Germany: coordinated expansion planning needed

By Leonard Göke, Claudia Kemfert, Mario Kendziorski, and Christian von Hirschhausen

ABSTRACT

Due to ambitious climate change targets and other energy and industrial policy goals such as the nuclear phase-out, the energy transition in Germany is heading toward a completely renewable energy system. This Weekly Report is the first to describe scenarios for 100 percent renewable energy coverage in Germany and, furthermore, shows it is both possible and realistic. In such a scenario, no more fossil fuels or nuclear energy would be used throughout Europe. With the available potentials, both electricity demand and overall energy demand can be covered by renewable energy. Due to electrification and sector coupling, electricity demand has doubled to around 1,200 terawatt hours. However, there have also been significant efficiency increases in the transportation and heating sectors. By taking grid expansion costs into account, power generating structures that are close to the load center would be strengthened compared to their state as of 2021. Despite more decentralized generation and storage structures, supply security would be guaranteed by integration into the European power grid. The perspective of a completely renewable energy system must be included in the planning of the entire energy system, including 100 percent renewable energy scenarios in German and European grid planning.

Tighter climate change targets in Germany are leading to a rapid increase in the use of renewable energy. A comprehensive renewable energy supply has been a significant goal of the *Energiewende* since the late 1970s.[1] In 2011, a completely renewable energy supply was first presented in detail in a report by the German Advisory Council on the Environment.[2] The possibility of a 100 percent renewable electricity and heat supply was confirmed in a report by the Fraunhofer Society in 2012.[3] Since then, the number of studies on the topic has increased significantly.[4] Following a recent German Federal Constitutional Court ruling on the necessity of a concrete plan for combating climate change as well as the subsequent National Climate Plan, the pressure to expand renewable energy sources in Germany has grown. This Weekly Report summarizes the current state of the discussion and describes scenarios for a completely renewable supply of energy for Germany by the 38 planning regions (NUTS-2 regions) in a European context.

Furthermore, it describes model scenarios in which renewable energy is used exclusively in Europe and in Germany. The importance of regional potentials as well as coordinating power generation planning and infrastructure planning are emphasized.[5]

1 Cf. Amory B. Lovins, *Soft Energy Paths: Towards a Durable Peace* (1979); as well as Florentin Krause, Hartmut Bossel, and Karl-Friedrich Müller-Reissmann, *Energiewende: Wachstum und Wohlstand ohne Erdöl und Uran* (1980) (in German).

2 Sachverständigenrat für Umweltfragen, "Wege zur 100 Prozent erneuerbaren Stromversorgung," Special Report (2011) (in German; available online, accessed on July 5, 2021. This applies to all other online sources in this report unless stated otherwise).

3 Hans-Martin Henning and Andreas Palzer, *100 Prozent Erneuerbare Energien für Strom und Wärme in Deutschland* (Fraunhofer-Institut für Solare Energiesysteme ISE, 2012) (in German; available online).

4 Tom W. Brown et al., "Response to 'Burden of Proof: A Comprehensive Review of the Feasibility of 100 percent Renewable-Electricity Systems," *Renewable and Sustainable Energy Reviews* 92 (2018): 834–847; Hans-Karl Bartholdsen et al., "Pathways for Germany's Low-Carbon Energy Transformation Towards 2050," *Energies* 12, no. 15 (2019): 2988; Claudia Kemfert, Christian Breyer, and Pao-Yu Oei, "100 percent Renewable Energy Transition: Pathways and Implementation," *Energies* Special Issue Introduction (2019); Pao-Yu Oei et al., "Lessons from Modeling 100 percent Renewable Scenarios Using GENeSYS-MOD," *Economics of Energy & Environmental Policy* 9, no. 1 (2020).

5 This Weekly Report is based on multiple studies, including Mario Kendziorski et al., "100 Prozent erneuerbare Energie für Deutschland unter besonderer Berücksichtigung von Dezentralität und räumlicher Verbrauchsnähe – Potenziale, Szenarien und Auswirkungen auf Netzinfrastrukturen," *DIW Politikberatung kompakt*, no. 167 (2021) (in German; available online).

DOI: https://doi.org/10.18723/diw_dwr:2021-29-1

Scenarios assess up to 100 percent renewable energy mix in Germany and Europe

Germany and the European Union (EU) are legally bound to meet the objective of climate neutrality. In addition, the share of renewable energy must increase significantly to reach the Paris climate targets. A completely renewable energy supply is best suited for achieving these goals, as neither fossil fuel technologies (with CO_2 capture hampered by uncertainties) nor nuclear energy are economically and ecologically viable solutions.[6] The scenarios in this report asses a renewable energy mix within Europe and take all sectors into consideration, such as energy, heating, and transportation (sector coupling).

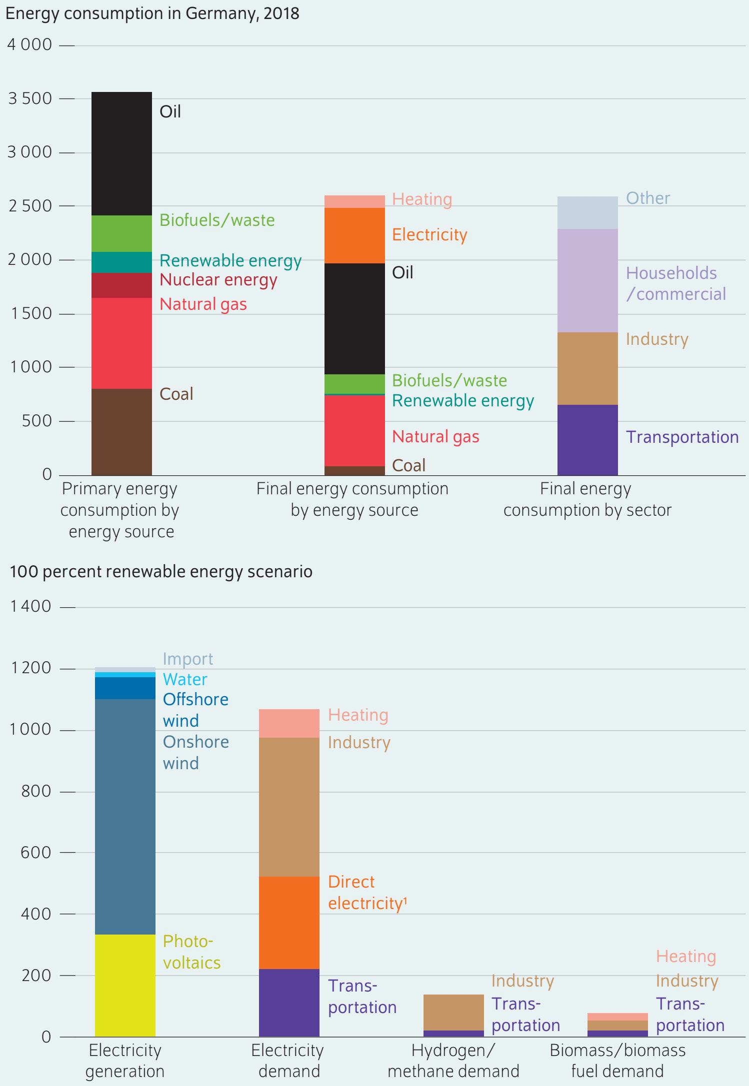
In the first step, a European decarbonization path towards a 100 percent renewable energy system is calculated at the country level. Both the data for the assumed available quantities of installed capacity for renewable energy sources and the underlying costs are based on the EU's "openENTRANCE" project.[7] In the scenarios, power generation is characterized by renewable technologies, such as photovoltaics (PV), onshore wind, and, depending on the country, offshore wind. In Central and Southern European countries, electricity is mainly generated by PV systems. Further north, the share generated by wind power increases. Battery storage, electrolyzers, and hydrogen turbines are being built all over Europe on a pro rata basis to ensure sufficient flexibility.

In the next step, investment decisions for the European counties (excluding Germany) are fixed and used as input variables for the next modeling run. Germany is no longer viewed as one large region. Instead, it is represented by 38 smaller regions, which enables a more detailed, decentralized mapping. The rest of the European countries can optimize their storage utilization but the investment decision no longer changes. In this way, the European dimension and its related flexibility are taken into account. Important parameters such as electricity and heat demand or the feed-in time series of variable renewable energy sources, such as wind and photovoltaic plants, thus differ spatially at a more granular level (Box).

Various technologies are available for designing the energy system, such as onshore and offshore wind power and photovoltaics as ground- and roof-mounted systems that produce primary energy in the form of electricity. Conventional electricity, space heating, process heating (mainly industry), mobility, and methane and hydrogen demand (for example, for aviation and shipping) must all be met. Inter-European exchanges of hydrogen or synthetic energy sources may take place, but imports from outside the continent are not taken into account. A combination of more recent potential estimates is used for this report: The upper limit for onshore wind is 223 gigawatts (GW) of installed capacity, the potential for offshore wind is 80 GW, and the upper limits for roof- and ground-mounted PV are 900 and 226 GW, respectively.[8] These were distributed to the individual regions using a GIS analysis and additionally divided into good, average, and poorer locations.

Figure 1

Energy consumption in Germany in 2018 and in the 100 percent renewable energy scenario (with sector coupling)
In terawatt hours



Source: Authors' own calculations.

In the 100 percent renewable energy scenario, most electricity is produced by onshore wind turbines. Over-all, the amount generated exceeds demand.

6 Cf. Karlo Hainsch et al., "Make the European Green Deal Real – Combining Climate Neutrality and Economic Recovery," *DIW Politikberatung kompakt*, no. 153 (2020) (available online).

7 Cf. Hans Auer et al., "Quantitative Scenarios for Low Carbon Futures of the Pan-European Energy System," Deliverable 3.1 (2020) (available online; accessed on June 23, 2021).

8 For the onshore wind potentials, cf. Thorsten Burandt, Konstantin Löffler, and Karlo Hainsch, "GENeSYS-MOD v2.0 – Enhancing the Global Energy System Model," *DIW Data Documentation*, no. 94 (2018) (available online). The PV potentials are based on Harry Wirt, *Aktuelle Fakten zur Photovoltaik in Deutschland*, (Fraunhofer ISE, 2021) (in German; available online; accessed on March 10, 2021).

Box

Methodology

The calculations in this report are based on the AnyMOD modeling framework developed at the Technical University of Berlin, which calculates both the European and the German energy system with a high temporal resolution and optimizes investment decisions in generation, conversion, and storage technologies as well as grid expansion.[1] Using a given energy demand and taking into account exogenously specified demands of sectors adjacent to the electricity sector (such as transportation demand or material demand in the industrial sector), the model determines a cost-optimal generation mix. Investments as well as the variable and fixed costs in the power generation, storage, and grid infrastructure are minimized while complying with the constraints, such as potential upper limits of technologies based on available space. Moreover, supply and demand are regionalized at the level of 38 regions. The existing electric and gas grid is set as the initial grid at the level of the national states and, for Germany, at the level of the 38 regions. The gas network can be used for hydrogen transportation due to additional investments. The exchange capacities between the European countries correspond to the TYNDP projects, which will be completed by 2025.

The additional demand arising from the decarbonization of all energy sectors is considered in the model used. As a result, this study includes not only the electricity sector, but the heating, industrial, and transportation sectors as well. Additionally, there is material demand for hydrogen and methane in industry or sectors that are difficult to electrify.

A majority of this demand must be covered by electricity generation, as the amount of biomass is limited and no imports of hydrogen or other energy sources from outside the EU are possible. In the model, electricity demand is accounted for hourly, space and industrial heating and transportation in four-hour blocks, and hydrogen and synthetic gas demand daily. In this way, it is possible to shift electricity demand from the sectors adjacent to the electricity sector and thus to map the flexibility that exists due to sector coupling. The model also has the option to invest in various electrical storage technologies, including batteries, which can efficiently store energy for a short period of time, and other energy storage devices that open up the possibility of storing energy for a longer period of time via electrolysis.

Further electrical storage technologies include pumped storage, which is limited to the current inventory, and compressed-air energy storage, which is generally less cost efficient than a combination of battery and hydrogen storage. Regional demand and feed-in time series provide a detailed mapping of the regional generation profile.

1 Cf. Leonard Göke, "anyMOD – A graph-based framework for energy system modelling with high levels of renewables and sector integration," Archive (2020) (available online; accessed on June 21, 2021).

Energy demand declining, but electricity demand on the rise due to sector coupling

How energy demand will develop in the future depends on a number of uncertainties, such as the extent of sector coupling, the development of conversion efficiency, and further energy consumption and behavioral adjustments. Overall, it is foreseeable that there will be efficiency gains as a result of the trend toward electrification, such as through the use of heat pumps or electromobility. This will reduce overall energy demand in the energy system compared to the system in 2021. The trend towards sector coupling is documented in a large number of current studies on the energy transition.[9]

Based on the European energy system model, Germany's electricity demand is 1,070 terawatt hours (TWh). Overall demand is based on 300 TWh of conventional electricity demand, 91 TWh of space heating, 223 TWh in transportation, and 456 TWh in industry (Figure 1). Additionally, there is exogenous demand for hydrogen and synthetic gas in the amount of 134 TWh and five TWh, respectively, in areas that are difficult to electrify, such as air and sea traffic, certain industrial processes, or the use of materials in conversion processes. Thus, the overall energy demand that the model must meet is 1,209 TWh. In comparison, final energy consumption in 2018 was 2,589 TWh.

Non-integrated vs. integrated: 100 percent renewable energy systems possible in both scenarios

As envisioned in the context of the sustainability targets, decarbonization implies a restructuring of the energy supply in terms of both the technologies used and its spatial structure. Unlike conventional energy sources, the costs and potentials of wind and solar-reliant systems depend strongly on their locations. An analysis of the relationship between the spatial structure of the power generation, flexibility options, and regionality is performed in two scenarios:

In the first case, only power generation technologies as well as electrical storage technologies are fixed. This is done under the assumption that there are no grid bottlenecks. This process roughly corresponds to the current planning process of the grid development plan. As a result, plants are more likely

9 Cf. Prognos, Öko-Institut, and Wuppertal-Institut, *Klimaneutrale Deutschland 2045. Wie Deutschland seine Klimaziele schon vor 2050 erreiche kann* (Agora Energiewende, 2021) (in German); Frank Sensfuß et al., *Langfristszenarien für die Transformation des Energiesystems in Deutschland 3* (2021) (in German; available online); and Wolf-Peter Schill, "Electricity Storage and the Renewable Energy Transition," *Joule* (August 2020): 2059-2064.

to be placed so as to produce the highest possible yield, as the distance to the consumers to be bridged is not priced in. This results in an increased need for grid expansion (in the following section, this is referred to as the "non-integrated" variant). The second variant considers investments in grid expansion and in power generation and storage capacities together ("integrated"). This results in a trade-off between the highest yield and the grid expansion costs required to achieve it. In such a process, the spatial components also play a role, as a location close to where consumption occurs can reduce additional grid expansion.

In both scenarios, a 100 percent renewable energy system can be calculated hourly. In both grid planning variants, a combination of onshore wind and solar PV (ground- and roof-mounted) dominates the power generation mix (Figure 2). In the non-integrated approach, offshore wind is added as a central large-scale plant; more infrastructure is required for this, and thus there is significantly less PV expansion. In contrast, in the integrated scenario, more solar plants are planned in the regions and the electricity generated is consumed more locally.

All regions have renewable energy potentials

The following section details the regional distribution of wind and PV installations as well as further installations in the integrated scenario (Table). There is a major need for additional wind turbines, especially in southern Germany. The balanced trade-off between additional investment in grid expansion, PV plants, or wind plants, even if they are located at sites with lower full load hours, results in a higher number of PV and wind plants that also match higher demand. As both the traditional electricity sector as well as the adjacent sectors whose electricity demand will grow in the future are represented in the modeling, the value of local generation increases. This is because the additional demand due to electromobility and space heating is generated directly on site.

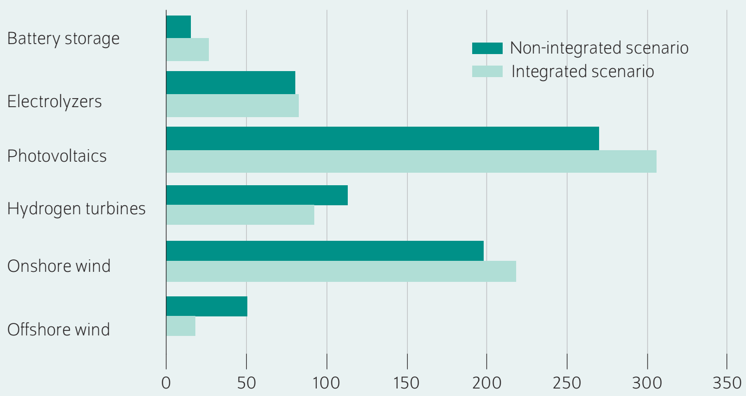
Hydrogen production, which is needed for seasonal storage and is used in other sectors, also tends to be regional. In the non-integrated scenario, in which many offshore wind plants are built, the installed capacity of electrolyzers is concentrated in the north. However, there are also electrolyzers in the rest of the country to siphon off excess production from renewable energy. With lower installed capacities of offshore wind power in the integrated scenario, there is no longer a concentration of electrolyzers in one location.

The model results confirm the assumption that when infrastructure costs are considered, power generation is closer to the load center and there is less need for grid infrastructure expansion. The integrated approach leads to stronger, equal regional distribution of generation and consumption. Integrated optimization that considers infrastructure costs leads to a more balanced exchange: The north-south divide is stronger in the non-integrated scenario while in the integrated scenario, almost all regions are closer to self-sufficiency in balance sheet terms.

Figure 2

Comparison of the expansion of generation technologies and storage options in both scenarios

In gigawatts



Source: Authors' own calculations.

In the integrated scenario, more photovoltaics and onshore wind plants are built.

Table

Regional distribution of generation and storage facilities in the integrated scenario

In gigawatts

Federal state	Onshore wind	Photovoltaics	Electrolyzers	Hydrogen turbines	Batteries
Baden-Württemberg	16.1	44.3	7.6	11.0	3.5
Bavaria	39.8	67.1	14.8	15.4	9.3
Brandenburg	17.7	21.2	6.6	5.5	1.6
Hesse	11.1	12.3	3.7	5.9	0.3
Mecklenburg-Western Pomerania	16.0	18.4	9.1	3.2	1.0
Lower Saxony	35.1	40.3	10.2	19.2	3.3
North Rhine-Westphalia	20.4	25.1	9.0	7.3	2.6
Rhineland-Palatinate	11.0	16.1	2.8	4.4	1.3
Saarland	1.3	1.7	0.9	1.1	0.3
Saxony	10.7	12.8	3.7	3.7	0.5
Saxony-Anhalt	19.4	23.0	7.4	6.2	1.5
Schleswig-Holstein	12.4	15.7	6.2	6.2	1.3
Thüringia	6.9	8.0	0.9	3.0	0.1

Note: The federal states of Berlin, Hamburg, and Bremen were incorporated into Brandenburg, Schleswig-Holestein, and Lower Saxony, respectively.

Source: Authors' own calculations.

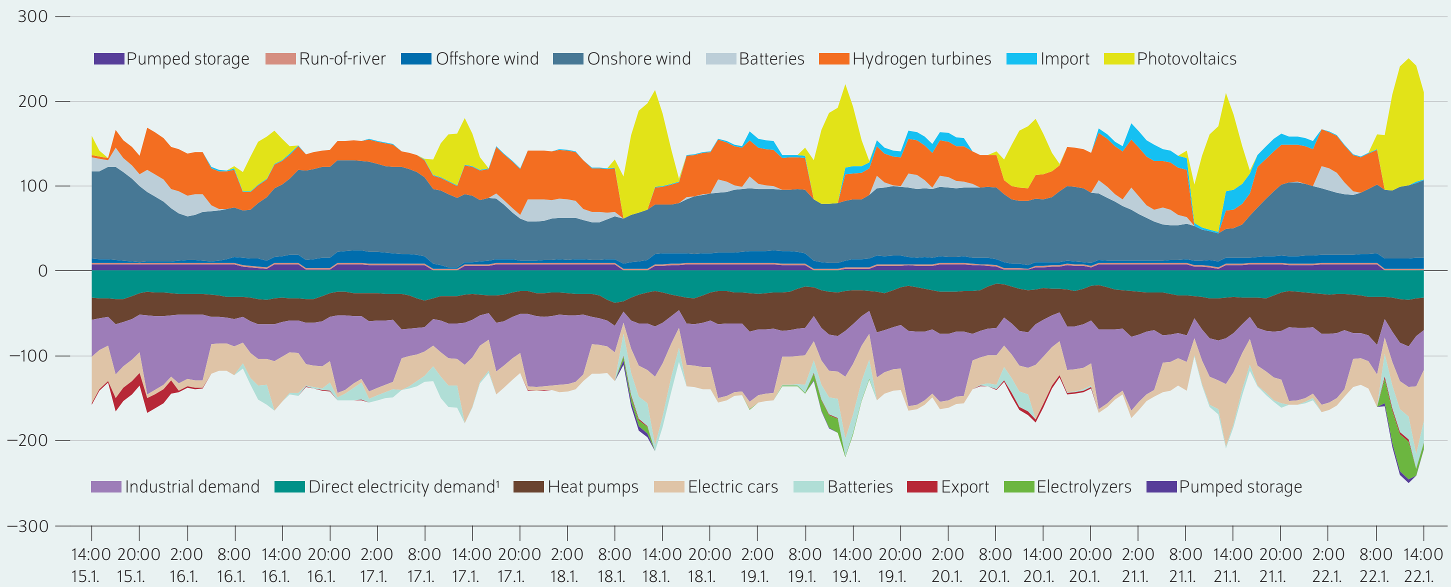
Supply security guaranteed even with complete substitution with renewable energy

Hourly supply security of the system is guaranteed even in a completely renewable energy system. Germany's integration into the interconnected system with neighboring countries plays an important role, as can be exemplified by the electricity generation and consumption for the time of lowest

Figure 3

Electricity supply and demand in Germany (hourly) at the time of the lowest feed-in of renewable energy sources

Model calculation for the integrated scenario, in gigawatts



1 Corresponds to direct electricity use primarily by households and commercial enterprises.

Source: Authors' own calculations.

Supply security is guaranteed even in a 100 percent renewable energy system.

feed-in from wind and PV in winter in the integrated scenario (Figure 3). The majority of electricity generation is from onshore wind turbines and is supplemented by feed-in quantities from PV systems at midday. When wind generation is low, demand is shifted when possible and is supported on the generation side by battery storage, hydrogen turbines, and imports from neighboring countries. While the feed-in of wind energy is high, all possible demands to be served are covered (for example, for electromobility or in industry) and batteries are charged to create a buffer. In these hours, a part of the electricity generated is exported to neighboring countries.

Incorporate 100 percent renewable scenarios when planning grids

Tighter climate change targets and the acceleration of renewable energy expansion also impact infrastructure planning. While CO_2 targets have been explicitly included in demand planning since the scenario framework in the 2015 grid development plan,[10] grid planning in both Germany and at a European level does not currently account for the possibility of a 100 percent renewable energy system. For example, the grid development plan in Germany is based on a high and even sometimes increasing share of fossil fuel power.

All scenario frameworks in the next grid development plan should contain 100 percent renewable scenarios, which has also been suggested in other comments on the grid development plan.[11] In the medium term, one goal should be coordinating all grid planning for electricity, natural gas, and hydrogen.

It is especially urgent to adjust infrastructure planning at a European level. Currently, the European Union's Ten-Year Network Development Plan (TYNDP) includes large amounts of fossil coal and natural gas as well as significant amounts of nuclear power.[12] Approaches to sustainable infrastructure planning are now available in the context of the pilot project PAC (Paris-compatible infrastructure scenarios), which proposes an almost exclusively renewable energy supply by 2040.[13] In the next step, these scenarios will be applied to the planning of Europe-wide infrastructure.

10 Cf. Robert Mieth et al., "Stromnetze und Klimaschutz: Neue Prämissen für die Netzplanung," *DIW Wochenbericht* no. 6 (2015): 91–96 (in German; available online).

11 Cf. Franziska Flachsbarth et al., *Kommentierung des ersten Entwurfs des Netzentwicklungsplans Strom 2035 (Version 2021)* (Öko-Institut, 2021) (in German; available online; accessed on June 21, 2021).

12 Entsog and Entso-E, *TYNDP 2020 Scenario Report* (2019) (available online; accessed on June 21, 2021).

13 Cf. CAN Europe and EEB, *Paris Agreement Compatible (PAC) – Scenarios for Energy Infrastructure* (2020) (available online; accessed on June 21, 2021).

Conclusion: using 100 percent renewable energy is possible and secure

Meeting climate change targets in a way that is cost-effective for the economy as a whole requires a 100 percent renewable energy supply in Germany. This Weekly Report shows that such an energy system is possible in the entire European Union, in Germany, and at the level of all 38 German planning regions. Non-European hydrogen imports, which will also use fossil fuels for the foreseeable future, are not necessary. The existing potentials in Germany's planning regions are sufficient, but must be developed much more actively.

The hourly supply security of a 100 percent renewable energy system would be guaranteed as long as flexibility options are utilized. Such options include integrating Germany into the interconnected grid, which would ensure electricity is exported in times of surpluses and imported to meet demand when needed.

Completely renewable energy system scenarios must be included in planning the overall energy system. This applies both to the arrangement of power generation and storage facilities and to the grid infrastructure. The next version of the scenario framework for the electrical grid development plan should include 100 percent renewable scenarios. This goes beyond Germany: Europe-wide, the switch from fossil power plants and nuclear power plants to renewable energy is important. Therefore, especially at the European level, adjusting the current ten-year development plans is particularly urgent, as they still envisage significant fossil fuel capacity and nuclear power.

Leonard Göke is a guest researcher at DIW Berlin | lgoeke@diw.de

Claudia Kemfert is Head of the Energy, Transportation, Environment Department at DIW Berlin | ckemfert@diw.de

Mario Kendziorski is a guest researcher at DIW Berlin | mkendziorski@diw.de

Christian von Hirschhausen is the research director of International Infrastucture Policy and Industrial Economics at DIW Berlin | chirschhausen@diw.de

JEL: Q54, I35, L94

Keywords: Renewable energy, sector coupling, energy planning

LEGAL AND EDITORIAL DETAILS

DIW BERLIN

DIW Berlin — Deutsches Institut für Wirtschaftsforschung e. V.
Mohrenstraße 58, 10117 Berlin
www.diw.de
Phone: +49 30 897 89–0 Fax: –200
Volume 11 July 28, 2021

Sale and distribution
DIW Berlin Leserservice, Postfach 74, 77649 Offenburg
leserservice@diw.de
Phone: +49 1806 14 00 50 25 (20 cents per phone call)

Layout
Roman Wilhelm, Stefanie Reeg, DIW Berlin

Cover design
© imageBROKER / Steffen Diemer

Composition
Satz-Rechen-Zentrum Hartmann + Heenemann GmbH & Co. KG, Berlin

ISSN 2568-7697