Beyond the Tipping Point

Flexibility gaps in future high-renewable energy systems in the U.K., Germany and Nordics

A Bloomberg New Energy Finance study commissioned by Eaton in partnership with the Renewable Energy Association

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Executive summary: tipping points (1)

Rapid technological improvements and increasing scale are driving down the costs of wind and solar generation, and of lithium-ion batteries for energy storage.

- Across Europe, the cost of generating energy for most wind and solar technologies is expected to more-than-halve from 2017 to 2040, according to BNEF's New Energy Outlook. This will drive the widespread adoption of these technologies, making them the largest source of electricity generation by the mid-2020s.
- Falling costs of lithium-ion batteries (li-ion) make battery use economic for a range of applications, from end-user storage to reducing peak system requirements.
- Cost reductions are driven by a variety of factors, which differ for each technology:
  - **Onshore wind** LCOE (levelized cost of electricity) falls from $66/MWh in 2017 to $35/MWh in 2040. The biggest share of cost reductions comes from increased utilization rates for new turbines, which can capture more energy from low wind speeds.
  - **Offshore wind** LCOE falls from $171/MWh in 2017 to $50/MWh in 2040. Reductions in installation costs, increased experience and bigger turbines drive cost down.
  - **Utility-scale solar PV** LCOE falls from $66/MWh in 2017 to $23/MWh in 2040. Falling PV module costs are the biggest driver of the decline in LCOE.
  - **Li-ion battery** prices fall from $273/kWh in 2017 to $73/kWh in 2030. Improvements in battery chemistry and manufacturing processes drive the cost decline.

These cost reductions will lead to three tipping points in the European energy system:

- **Tipping point 1** is when wind and solar become the cheapest option for *new* power generation. In most of Europe, this tipping point has already been reached – these two technologies are already cheaper than building new gas or coal plants, making them the lowest-cost options for new electricity supply.
- **Tipping point 2** comes when energy from new-build wind and solar become cheaper than that from *existing* fossil capacity. By the end of the 2020s, most wind and solar project lifetime costs are expected to be lower than the cost of continuing to run existing gas and coal plants.
- **Tipping point 3** is when rooftop PV systems become cheaper than buying energy from the grid via a retailer. Much of Europe has crossed this economic tipping point, and additions will in future be driven by consumer adoption, local regulatory frameworks and availability of rooftops.
  - The date at which adding a battery to such systems starts to make economic sense will vary by country, depending on the solar resource, the retail power tariff and its structure, and the availability of complementary value streams for the storage system.

Executive summary: tipping points (2)

The tipping points will lead to radical changes in the European power system mix. These changes come quickly, but not overnight.

- A 2% drop in electricity demand over 2017-30 puts a damper on investment.
- After 2030, electric vehicles will help demand grow again, with EVs reaching a 12% share of consumption in 2040. This will create need for new capacity, but not in all European markets.
- The need to meet peak demand means some gas and coal plants are kept online to provide energy on wind-still, cloudy days. This reduces the need for new capacity, slowing investment in new wind and solar.

In the United Kingdom, wind and solar alone could account for 39% of power generation by 2030, and 50% by 2040.

- According to BNEF's New Energy Outlook, wind and solar capacity in the United Kingdom will grow by 45GW over 2017-40.
- The U.K. adds 25GW of wind capacity over 2017-40. Capacity additions to 2027 are led by subsidized offshore wind. But over 2028-40, the U.K. adds 13GW of onshore wind economically, as favorable wind speeds and growing electricity demand make it the cheapest option.
- Over the same period, the U.K. adds 20GW of solar PV. However, a relatively poor solar resource means that these panels contribute little to generation – about 8% in 2040 – even though they become the cheapest source of energy by the mid 2030s.

In Germany, wind and solar could account for 47% of power generation by 2030, and 61% by 2040

- Wind and solar capacity in Germany grows by 127GW over 2017-40 on the back of widespread solar PV deployment.
- Germany adds 108GW of solar PV capacity over 2017-40. The growth comes primarily from small-scale PV installations, driven by high retail prices and an availability of rooftops.
- Wind capacity over the same period grows by a mere 18GW. Falling demand and vast solar additions limit the deployment of wind, which grows to around 80GW in 2024 and stabilizes around that level after that.
- Relatively new, high-efficiency coal and lignite plants mean Germany keeps around 50GW of fossil fuel capacity online in 2040, compared to 71GW in 2017.

In the Nordic markets (Norway, Sweden, Denmark and Finland), wind and solar could account for 15% of power generation by 2030, and 11% by 2040

- Wind and solar capacity in the Nordics remains stable over 2017-40, as the region makes good used of its vast hydro capacity.
- Nordic hydro stands at 51GW in 2017, making up almost half of installed capacity and generating two thirds of the region's electricity needs.
- As a result, the Nordics add just 6GW of solar capacity and 2GW of offshore wind capacity. Onshore wind capacity shrinks by 6GW as older wind farms reach the end of their technical life and are not replaced.

Executive summary: United Kingdom (1)

BNEF's New Energy Outlook forecasts a U.K. energy system increasingly dominated by renewable energy, thanks to rapidly falling costs

- Renewables represent more than half of the U.K.'s power supply by 2026, according to NEO 2017. By 2040, some 63% of power is generated from renewable sources.
- Low-cost, variable wind and solar resources could account for 40% of power generation as soon as 2030, and 50% by 2040.

Renewable energy will meet more of the U.K.'s demand, more often

- In 2017, variable renewable generation (wind and solar) rarely meets more than 25% of hourly demand.
- In 2040, these resources contribute to more than 49% of hourly demand for over half of the year.

At certain times, and with increasing frequency, wind and solar energy alone could exceed total demand

- In 2030, less than 1% of wind and solar generation is curtailed or 'wasted'. By 2040, this rises to 3%, with almost 750 hours when output exceeds demand – the equivalent of roughly one month. (These figures do not account for grid and other constraints, which could lead to much higher levels of curtailment.)
- There will be growing opportunities for energy storage technologies, or flexible demand such as electric vehicle charging and industrial processes, to make use of surplus renewable energy. Interconnections will also play an important role, to allow export when needed.

System volatility will increase markedly

- As wind and solar production rises and falls, other flexible resources will need to ramp up or down to balance them from hour to hour. The need is greatest at times when demand is also rising or falling.
- According to our modeling, in 2017 the maximum ramp rates are 10GW/hour up and 11GW/hour down. This represents roughly one-third of the U.K. gas fleet turning on or off in an hour.
- By 2040, the highest ramps will be 21GW up and 25GW down – equivalent to around 20-25% of the U.K.'s *entire generation fleet* turning on or off in one hour.
- There will be increasing opportunities for fast-ramping resources, such as energy storage, certain types of demand response, and gas generators, to support needed levels of ramping. Extreme ramp rates are likely to stress the system and also cause conventional generators to operate less efficiently; flexible demand and storage may be able to help mitigate these impacts.

'Baseload' resources will struggle to stay in the picture

- The increase in volatility means that as early as 2030, there are whole weeks where wind and solar generation exceeds demand at some point every day. This leaves no room for 'baseload' technologies that need to run flat-out, such as nuclear power.

Executive summary: United Kingdom (2)

There will be entire days and even weeks when total renewable energy supply exceeds demand

- Due to the dominance of wind power in the U.K., the highest wind and solar output periods are during winter, when the wind blows the most. However, demand is lower in summer, which means the share of wind and solar throughout the year remains relatively constant.
- By 2040, the highest wind and solar output week will see almost as much generation from these sources as total demand. While wind and solar do not match demand in every hour, they do provide enough energy in total in these weeks, and there is opportunity for energy storage to help match supply and demand.
- As the timeframe increases, generation from variable renewables moves closer to the yearly average. The highest-output month sees wind and solar generation equivalent to 70% of demand.

However, there will also be days, weeks and even months when the majority of demand must be met by other sources

- Relatively still, cloudy periods can last for many days in the U.K., and there can be hours with virtually no wind and solar generation.
- While these periods occur throughout the year, they are most common during summer, when wind is lowest.
- Even in 2040, we see entire weeks and months where non-wind/solar generation meets 80% and 72% of demand, respectively.

As a result, the total back-up capacity needed in 2040 is much the same as in 2017, despite the growth in wind and solar

- 70GW of dispatchable resources (generation, storage, flexible demand, interconnectors) are needed in 2040 to meet peak demand during periods of low wind and solar generation.
- But the back-up capacity will be used less and less often. Average utilization of non-wind and solar capacity falls from more than 50% in 2017 to 29% in 2040. This will hurt the economics of certain plants, mainly combined cycle gas turbines.

A future U.K. energy system dominated by variable renewable energy must be complemented by flexible resources

- Battery storage technologies and flexible demand are well-placed to solve short-term volatility issues arising from renewables, e.g. shifting energy from one hour to another within a day; or even shifting energy from one day to another within a week.
- However, these technologies will not be well-suited to providing back-up for weeks and months when wind and solar resources are insufficient to meet demand. To meet these longer-term gaps will require dispatchable and, ideally, flexible sources. Currently, only pumped hydro, interconnectors and gas generation can do this economically. Other technologies such as hydrogen storage would require significant cost reductions.
- Still, even at about 50% wind and solar, the opportunities and need for inter-seasonal storage are limited. Short-term storage provides most of the flexibility the system requires at this level of wind and solar penetration.

Executive summary: Germany (1)

BNEF's New Energy Outlook forecasts a German energy system increasingly dominated by renewable energy, thanks to rapidly falling costs

- Renewables represent more than half of Germany's power supply by 2022, according to NEO 2017. By 2040, some 74% of electricity is generated from renewable sources.
- Low-cost, variable wind and solar resources could account for 49% of power generation as soon as 2030, and 61% by 2040.

Renewable energy will meet more of Germany's demand, more often

- In 2017, variable renewable generation (wind and solar) rarely meets more than 37% of hourly demand.
- In 2040, these resources contribute to more than 71% of hourly demand for over half of the year.

At certain times, and with increasing frequency, wind and solar energy alone could exceed total demand

- In 2030,some 3% of wind and solar generation is curtailed or 'wasted'. By 2040, this rises to 16%, with over 2,300 hours when output exceeds demand – roughly one fourth of the year. (These figures do not account for grid and other constraints, which could lead to much higher levels of curtailment.)
- There will be growing opportunities for energy storage technologies, or flexible demand such as electric vehicle charging and industrial processes, to make use of surplus renewable energy. Interconnections will also play an important role, to allow export when needed.

System volatility will increase markedly

- As wind and solar production rise and fall, other flexible resources will need to ramp up or down to balance them from hour to hour. The need is greatest at times when demand is also rising or falling.
- According to our modeling, in 2017 the maximum ramp rates are 13GW/hour up and 11GW/hour down. This represents nearly half of the German gas fleet turning on or off in an hour.
- By 2040, the highest ramps will be 38GW up and 34GW down – equivalent to around 40% of Germany's *dispatchable generation fleet* turning on or off in one hour.
- There will be increasing opportunities for fast-ramping resources, such as energy storage, certain types of demand response, and gas generators, to support needed levels of ramping. Extreme ramp rates are likely to stress the system and also cause conventional generators to operate less efficiently; flexible demand and storage may be able to help mitigate these impacts.

'Baseload' resources will struggle to stay in the picture

- The increase in volatility means that as early as 2030, there are whole weeks where wind and solar generation exceeds demand at some point every day. This creates a very challenging environment for 'baseload' technologies that benefit from running at a constant stable output, such as coal and lignite.

Executive summary: Germany (2)

There will be entire days and even weeks when total renewable energy supply exceeds demand

- Currently in Germany, the highest wind and solar output periods are during winter, when the wind blows the most. However, this changes as more solar is deployed. By 2040, summer output is on a par with winter. The share of wind and solar generation is high in winter and, due to lower demand, also in the summer.
- By 2040, the highest wind and solar output week will see more generation from these sources than total demand. While wind and solar do not match demand in every hour, they do provide enough energy in total in these weeks, and there is opportunity for energy storage and flexible demand to help match supply and demand.
- As the timeframe lengthens, generation from variable renewables moves closer to the yearly average. The highest-output month sees wind and solar generation equivalent to 78% of demand.

However, there will also be days, weeks and even months when the majority of demand must be met by other sources

- Relatively still, cloudy periods can last for many days in Germany, and there can occasionally be hours with virtually no wind and solar generation.
- While these periods occur throughout the year, they are most common during autumn and late winter, when wind is lower than winter and the sun does not shine as much as in summer.
- Even in 2040, we see entire weeks and months where non-wind/solar generation must meet 85% and 63% of demand, respectively.

As a result, the total back-up capacity needed in 2040 is much the same as in 2017, despite the growth in wind and solar

- 97GW of dispatchable resources (generation, storage, flexible demand, interconnectors) are needed in 2040 to meet peak demand during periods of low wind and solar generation.
- But the back-up capacity will be used less and less often. Average utilization of non-wind and solar capacity falls from around 51% in 2017 to 27% in 2040. This will hurt the economics of certain plants, such as coal and gas.

A future German energy system dominated by variable renewable energy must be complemented by flexible resources

- Battery technologies and flexible demand are well-placed to solve short-term volatility issues arising from renewables, e.g. shifting energy from hour to hour or day to day. By 2040, Germany has a significant amount of solar capacity, creating an opportunity for daily storage to shift energy from day to night.
- However, these technologies will not be well-suited to providing back-up for weeks and months when wind and solar resources are insufficient to meet demand. To meet these longer-term gaps will require dispatchable, and ideally flexible sources. Currently, only pumped hydro, interconnectors and gas generation can do this economically. Other technologies such as hydrogen storage would require significant cost reductions.
- Still, even at around 60% wind and solar in Germany, there is no need for inter-seasonal storage. Short-term storage and other generation sources provide enough flexibility to balance the system.

Executive summary: Nordics (1)

In this report, we define the Nordics as Denmark, Finland, Norway and Sweden.

BNEF's New Energy Outlook forecasts a Nordic energy system dominated by hydro, despite the falling costs of wind and solar

- This is unlike other European countries that see significant deployment of wind and solar due to rapidly falling costs.
- Renewables, including hydro, already represent nearly three quarters of the Nordics' power supply. By 2040, some 78% of electricity is generated from renewable sources, 67% by hydro alone.
- Low-cost, variable wind and solar resources could grow to 15% of power generation as soon as 2030, but then fall back to 11% by 2040 as some capacity retires and is not replaced in the absence of subsidies.

Wind and solar play a relatively small role in meeting Nordic demand

- In 2017, variable renewable generation (wind and solar) rarely meets more than 17% of hourly demand. This number increases to 24% in 2030.
- However, by 2040, these resources fall back, reaching virtually the same levels as in 2017, albeit with more solar and less wind.

Wind and solar energy never exceed total demand in 2030 or 2040

- Curtailment, or 'wasted' energy, due to wind and solar output exceeding demand, will not become an issue in the Nordics. (These figures do not account for grid and other constraints between and within Nord Pool bidding areas. These could lead to higher levels of curtailment.)

As a result of relatively low wind/solar penetration, the Nordics do not experience significant growth in system volatility

- At the relatively low penetration of wind and solar in the Nordics, volatility does not change significantly from current levels.
- According to our modeling, in 2017 the maximum ramp rates are 8GW/hour up and 6GW/hour down. This represents about one-sixth of the Nordic hydro fleet turning on or off in an hour.
- By 2040, the highest ramps will be 5GW up and 3GW down – some 37-50% lower than today.
- The vast availability of hydro resources is well-suited to dealing with the ramping requirements in the Nordics. However, local flexibility resources could still be required in case of volatility either in regions remote from hydro stations, or connected via occasionally-congested transmission lines.

Executive summary: Nordics (2)

Unlike other European power systems, which undergo massive changes as wind and solar grow, the Nordics market remains relatively unchanged

- The relatively small addition of wind and solar capacity will not have a significant impact on the overall structure and operation of the generation fleet.
- Because hydropower is so dominant, a 78% renewable (11% solar and wind) scenario in 2040 is achieved without introducing large amounts of volatility and curtailment. There is still room for baseload resources that are always on.

The periods of highest and lowest wind and solar output complement hydro resources

- The hydrological cycle in the Nordics is such that water inflow is at its lowest during winter, when water is mostly frozen, and at its highest during spring and summer, when snow melts.
- The opposite is true of wind power, which is higher over the winter when demand is high, and lower over the summer.
- The complementary nature of wind and hydro makes wind a good fit for the Nordic power system.

Thanks to Norwegian and Swedish hydropower, the Nordics have the flexible resources required to accommodate variable renewables – and even have flexibility to spare

- Although we have analysed the Nordics as a single market, in actual fact the majority of hydro resources are in Norway and Sweden.
- These resources allow the region as a whole to both achieve deep decarbonization, and introduce variable wind and solar capacity without encountering system flexibility issues.
- The Nordics are thus in a privileged position to be able to take advantage of cheap wind and solar, reducing the need for other types of capacity and energy – including additional storage technologies. (Note that this assumes strong interconnection between Nordic countries.)
- In fact, our analysis indicates that there is more than enough flexible hydro capacity to deal with the variability of wind and solar. This presents an opportunity for increased interconnections to other European countries such as the U.K. and Germany, so that Nordic hydro can provide additional flexibility in those markets where wind and solar may reach much higher penetration.

Summary implications

U.K. and Germany

- In our analysis, the U.K. and German energy systems will share many of the same characteristics. These are a rapidly growing proportion of wind and solar in overall generation; increasing system volatility; a growing excess of renewable energy at certain times; and growing variabililty of wind and solar output over days, weeks and months where these may generate a lot or very little.
- There are some contrasts, however:
  - We find greater opportunities in Germany for energy shifting over multiple durations. Germany reaches a higher penetration of wind and solar, equivalent to 61% of demand in 2040, versus 50% for the U.K. This means that most of the effects described above are felt more keenly in Germany. For example, in 2040 16% of wind and solar is curtailed in Germany, compared with just 3% in the U.K.
  - Germany has more solar; in fact, in 2040, solar is forecast to have roughly double the capacity of wind (onshore and offshore) in that country. The U.K. is predicted then to have more wind capacity than solar. This means that much of Germany's curtailment happens during concentrated parts of the day in sunnier months from April to September, providing greater opportunities for day-night storage or demand shifting.

The Nordics

- Our Nordics analysis reveals an energy system that will undergo far less change than the U.K. or Germany, and face fewer challenges. On an economic basis, wind and solar in 2040 may not generate much more than they do today.
- Although our analysis did not consider the possibility of transfers of energy and flexibility between the three regions, it is clear that the challenges presented in the Germany and U.K. sections of this report will create opportunities for the Nordics – Norway and Sweden in particular – to provide flexibility to other parts of the European energy system.

Further analysis

- This analysis was focused on understanding the flexibility challenges that may occur after the renewables 'tipping point' is reached. Our future analysis will focus on the possible solutions and opportunities, including the following:
- Opportunities for storage and flexible demand: as battery costs fall, transport becomes electrified and demand management technologies improve, these will play a larger role in energy system flexibility, complementing flexible generation.
- Greater interconnection and coordination: as power markets and grids become more closely coupled, there will be greater opportunities for neighboring power systems to provide complementary support to each other.
- Power market design and policy approaches: the changes described in this report are structural and fundamental to how the power markets and grids will operate in future. Policy and regulatory approaches are already beginning to adapt.
- Pushing beyond 50-60%: the issues described in this report will expand and evolve as the power system is decarbonized beyond the 50-60% range, and as decentralized energy resources gain market share.

Important terms

- **Learning rate**: this is the relative fall in costs for every doubling of capacity. For example, a learning rate of 29% for solar modules means that for every doubling of installed PV capacity the price drops 29%.

- **Behind-the-meter**: an energy asset on a consumer site, used to help meet the consumer's energy demand. This allows the consumer to avoid purchasing retail energy when the energy from the asset is used to meet demand instead, and potentially to sell energy back to the grid. These assets are physically behind the customer's energy meter, so that any of the consumer's demand they meet is perceived by that consumer's supplier as a reduction in demand. Solar systems or batteries, placed in residential or commercial spaces are good examples of such generators.

- **Socket parity**: a metric used for behind-the-meter generation systems. Parity is reached when the levelized cost of energy (LCOE) of such a system is equal to the cost of the energy from the grid that it is able to offset.

- **Variable renewables**: these are sources of renewable energy whose generation varies with resource availability and cannot be scheduled on demand. In this report, this includes onshore wind, offshore wind, and large and small-scale solar.

- **Levelized cost of electricity**: this is defined as the minimum tariff (in $/MWh on the day the project commences operation) required to achieve a nominal hurdle internal rate of return. In other words, it is the required nominal revenue of a project per unit of electricity generated to pay back the initial investment and cost of capital over the project's lifetime.

- **'Europe':** in this report, this refers to EU28, plus Switzerland and Norway.

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Forecasts used in this study

Extracts from BNEF's New Energy Outlook

What is BNEF's New Energy Outlook and how to interpret it

What is BNEF's New Energy Outlook

- BNEF's New Energy Outlook (NEO) is an annual modeling exercise focused on the electricity sector. Its goal is to provide a unique assessment of the economic drivers and tipping points that will shape the sector to 2040.
- Some 65 in-house technology and country specialists contribute to the inputs and analysis that make up the final report.
- In the short term, market projections are based on an assessment of policy drivers. BNEF's proprietary project database is also used to provide a detailed understanding of planned new build, retrofits and retirements, by country and sector.
- In the long run, NEO assumes no new policies. For example, once renewable subsidy regimes expire, they are not renewed. For Europe, the last subsidized projects come online in 2025 (U.K. offshore wind). Similarly, we do not assume that new policies will be enacted to meet the Paris Agreement goals, as no policies to that end exist today.
- As such, long-term capacity built according to NEO is deployed on pure economical considerations.

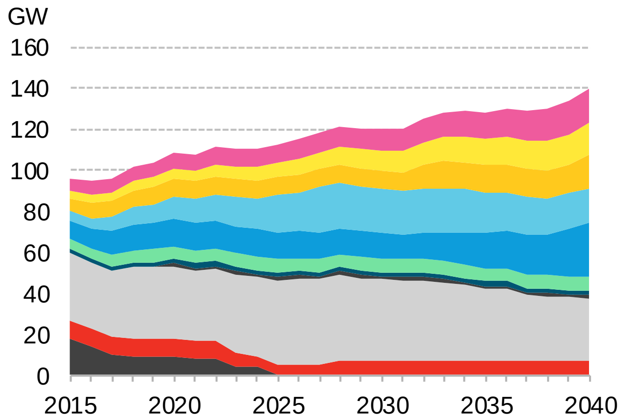
How to interpret BNEF's New Energy Outlook

- The objective of NEO is not to provide a political document or a BNEF house view, but to highlight:
  - The changing fundamentals of renewable and conventional energy
  - The implication of these changes on the electricity sector
  - The future risks and opportunities that arise from the changing landscape
- The system that NEO forecasts to 2040 is based on a least-cost assumption. Hence, NEO delivers the cheapest system that satisfies the following two conditions:
  - There is enough energy to meet demand over the year
  - There is enough capacity to meet peak demand
- As such, for the NEO outlook to materialize would require significant market reform and new price signals to maximize the value from new technologies.
- The New Energy Outlook is published in seven volumes – Global Synthesis, Americas, EMEA, Asia Pacific, Wind, Solar, and Fossil Fuels.

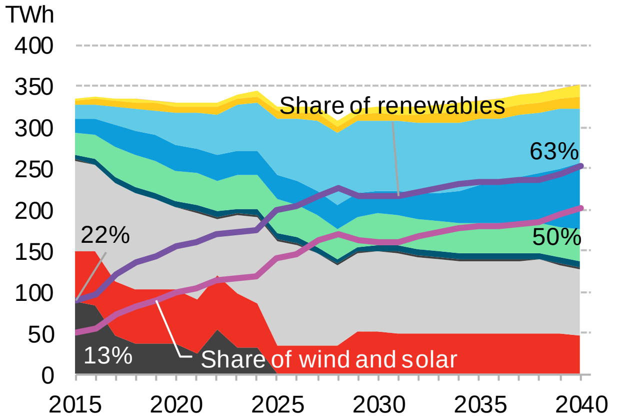
Forecasts for U.K., Germany and Nordics

United Kingdom

Cumulative installed capacity

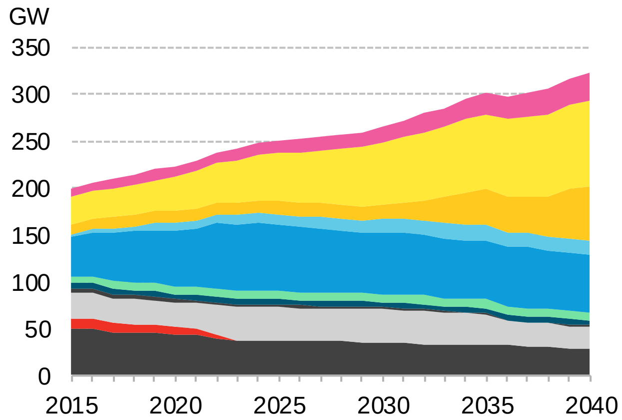


Electricity generation

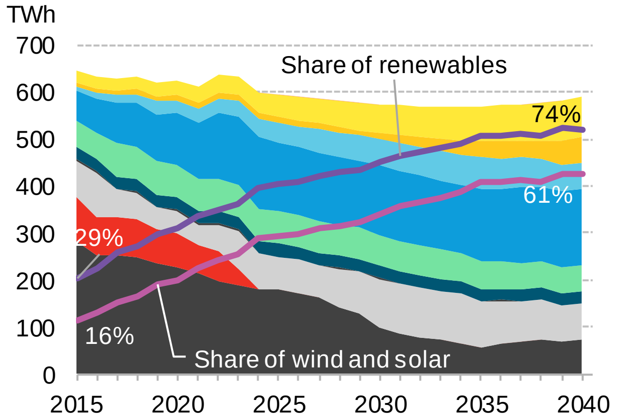


Germany

Cumulative installed capacity

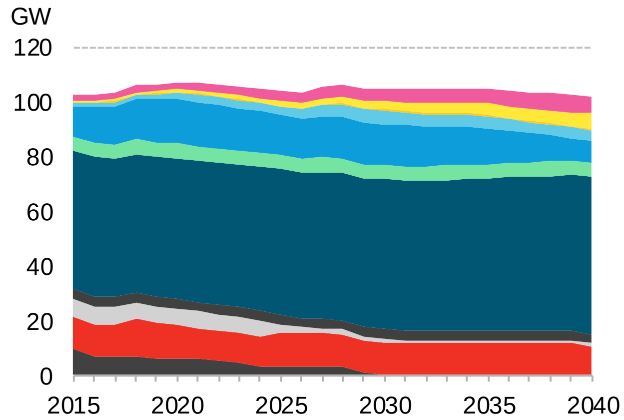


Electricity generation

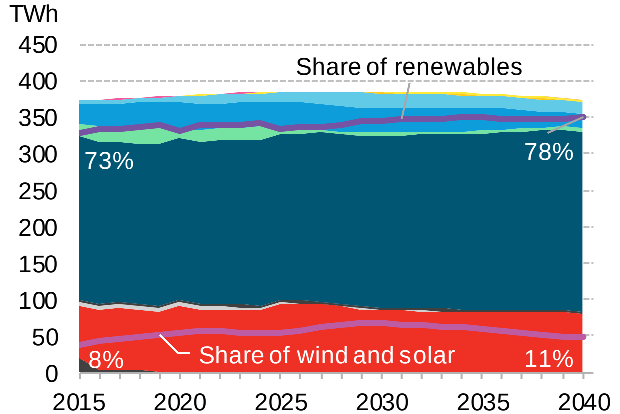


Nordics

Cumulative installed capacity



Electricity generation



Coal | Nuclear | Gas | Oil | Other | Hydro | Biomass | Onshore wind | Offshore wind | Utility-scale PV | Small-scale PV | Flex

Forecasts for U.K., Germany and Nordics

United Kingdom

- The U.K.'s installed generating capacity grows 45% over 2017-40, on the back of a 45GW mix of subsidized and economic wind and solar build.
- Gas capacity, which is supported by the UK's capacity market, initially grows from 21GW in 2017, to a peak of 42GW in 2026. After that, cheap new storage technologies displace gas, which shrinks to 31GW by 2040.
- The share of wind and solar in the U.K. generation mix grows from 18% in 2017 to 40% in 2027.
  - This initial steep increase is driven by subsidized growth in offshore wind capacity, from 7GW to 22GW.
- After 2027, wind and solar growth slows. Retiring offshore wind farms are replaced by onshore wind and solar, which have a lower energy yield. As a result, the share of wind and solar grows gently, reaching 50% by 2040.

Germany

- Germany's installed capacity grows 54% over 2017-40, on the back of 62GW of small-scale PV additions. Another 46GW of utility-scale solar is deployed, while wind capacity grows by a more modest 18GW.
- Coal and gas capacity shrinks by just 20GW over 2017-40. As wind and solar power becomes cheaper, some fossil fuel plants get crowded out. Eventually, these shut due to age or economics, the energy they used to generate replaced by renewables.
- The share of wind and solar in the German generation mix grows substantially, from 16% today to 61% in 2040.
  - Most of this growth comes from wind, with its higher capacity factors, despite solar capacity additions significantly outpacing wind.

Nordics

- Nordic installed capacity stays flat over 2017-40, at 103GW. The region's 51GW of hydro capacity grows by 8GW to 2040, leaving little space for growth in other technologies.
- Coal and gas capacity, of which there is already very little, shrinks from 13GW in 2017 to 1GW in 2040. The region weans itself off coal by 2030, as poor economics drive the last few plants offline.
- The region has little space for other technologies. Combined wind capacity shrinks by 4GW over 2017-40, while solar grows by 5GW, mainly due to small-scale system additions.
- More than 70% of electricity in the Nordics is already supplied by renewables. Hydro alone accounts for 58%. Limited growth in wind and solar means these two technologies push their share up from 10% in 2017 to 11% in 2040.

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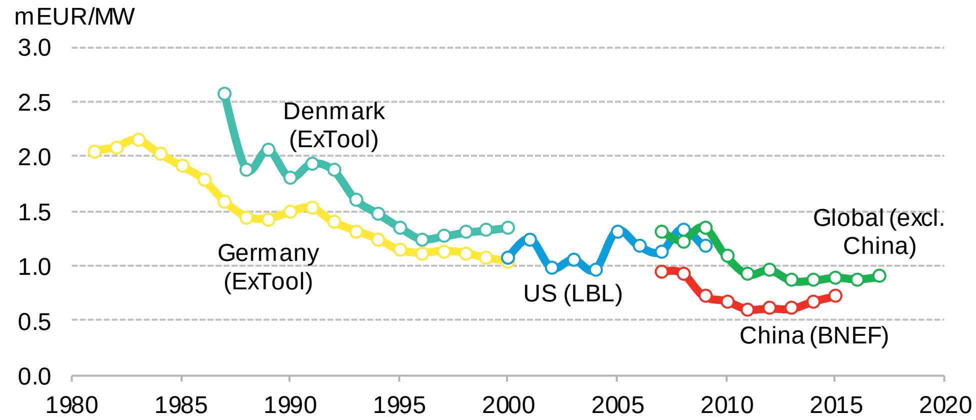
The future cost of wind, solar, and storage

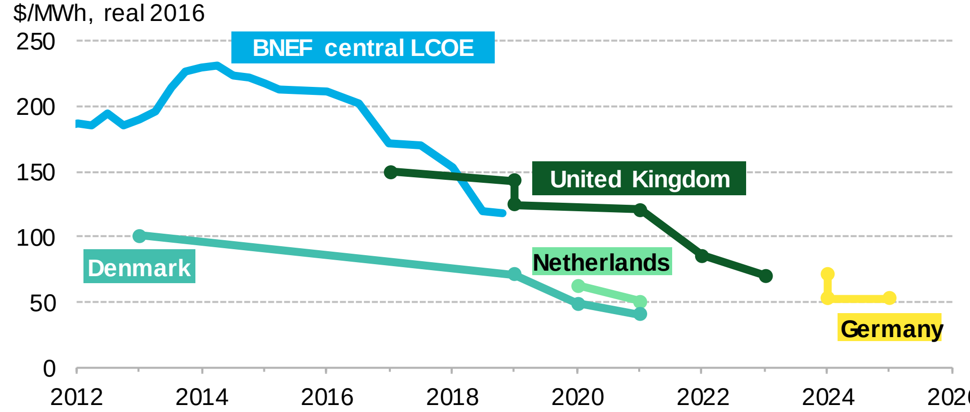
Historical and future cost drivers

Levelized cost of energy for onshore and offshore wind

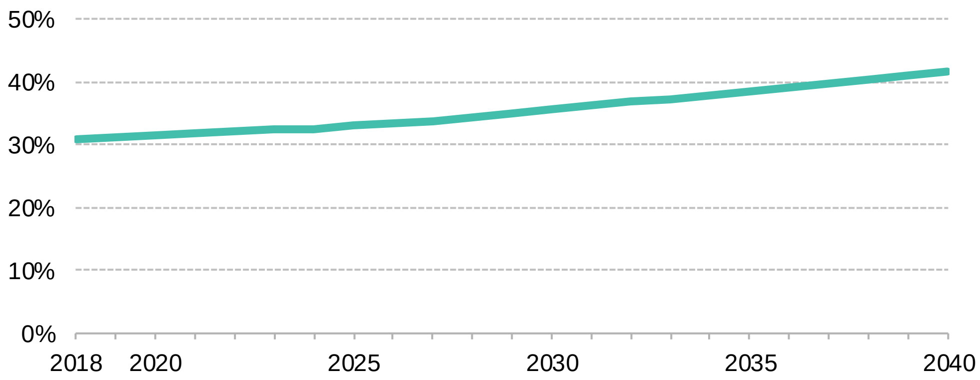
Historical onshore wind turbine costs



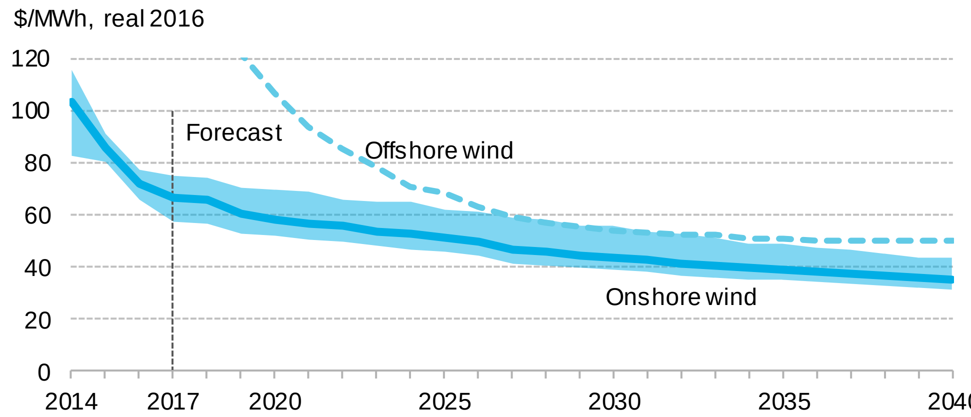
Levelized bids of completed offshore wind auctions by delivery year



Forecast of new onshore wind capacity factors



LCOE forecast for onshore and offshore wind, Europe



Source: Bloomberg New Energy Finance

Levelized cost of energy for onshore and offshore wind

Historical

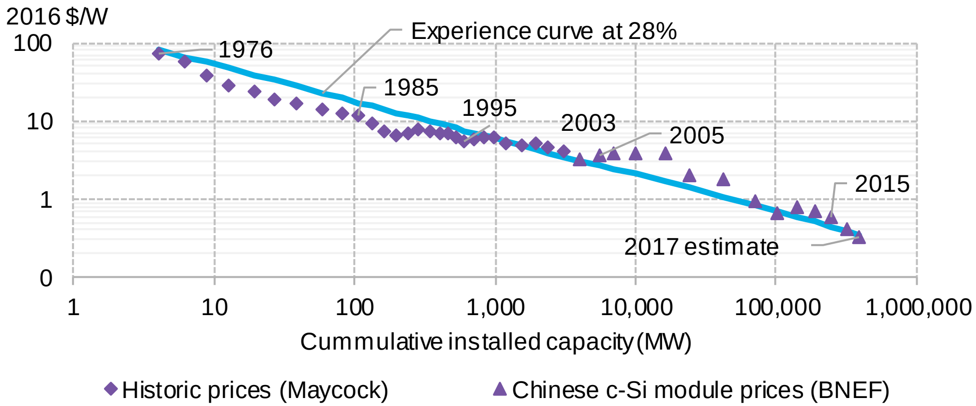
- Costs for onshore and offshore wind have been decreasing steadily over the past years. Competitive auctions and industry consolidation have brought major changes to the sector.
- **Onshore wind**: costs for turbines have dropped steadily around the globe, going from around 1.3 million euros per MW in 2007 to 0.9 million euros per MW in 2017. This translates to a learning rate of 9%, itself the result of the cost per turbine remaining stable, or falling, while their power output grows. Other cost drivers include:
  - **Smarter operation and maintenance** schedules tailored to specific site needs, bringing operating costs down.
  - **Financing experience** allowing lower-cost capital to be directed to the construction of onshore wind.
- **Offshore wind**: total costs for offshore wind projects have dropped dramatically in the last few years, and may go below $50/MWh in the 2020s – as suggested by auctions in Germany and Denmark. The move to competitive auction bidding for subsidies allowed better price exploration, contributing to the quick drop in price. Other cost drivers include:
  - **Increased experience** for developers reducing construction risk and developing a robust supply chain, driving installation costs and times down.
  - **Larger projects** allow developers to capitalize on economies of scale.

Future

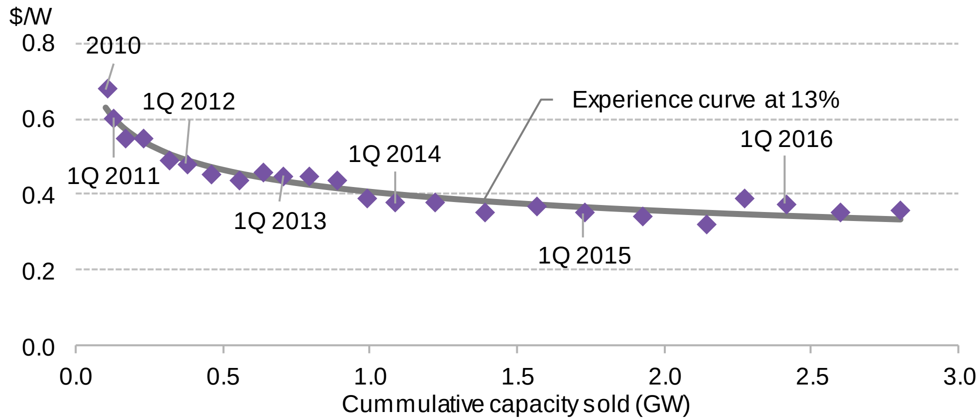
- Future cost declines for power from onshore and offshore wind come from technology and efficiency improvements rather than drops in the costs of inputs, including:
  - **Turbine size**: onshore wind turbines have gone from 1.6MW in 2007 to 2.5MW in 2017, and are expected to grow further. Similarly, offshore wind turbines are expected to grow from 8MW today to as much as 15MW by the mid 2020s.
  - **Improved capacity factors**: onshore wind capacity factors are expected to increase as turbines are made to fit site characteristics better.
  - **Maintenance costs**: we expect onshore wind maintenance costs to drop another 12% by 2025.
- LCOEs for both onshore and offshore wind drop significantly over 2017-40 as a result of these dynamics.
  - ***Onshore wind: the European LCOE goes from $66/MWh in 2017 to $35/MWh in 2040.***
  - ***Offshore wind: the European LCOE will drop by around 70% over 2017-30 to $53/MWh, stabilizing after that.***

Levelized cost of energy for utility-scale and small-scale solar

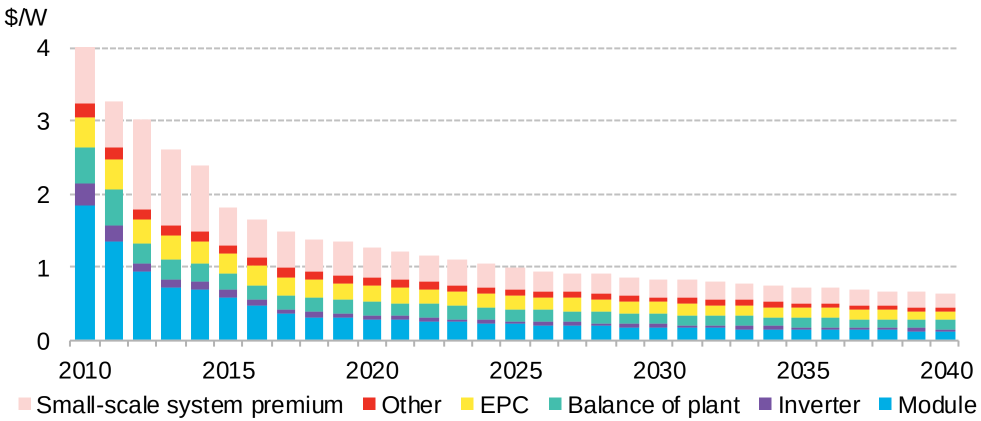
Historical PV module costs and experience curve



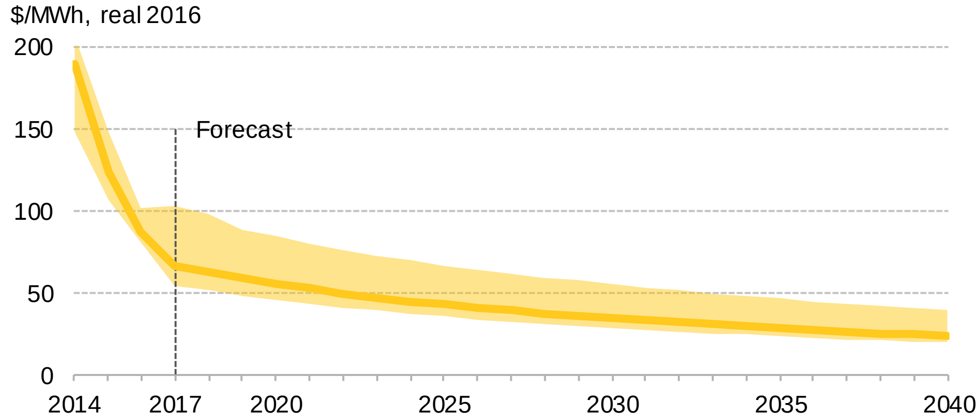
Experience curve for micro-inverter manufacturer Enphase



BNEF global benchmark capex forecast for fixed-axis systems



LCOE forecast for utility-scale PV, Europe range



Source: Bloomberg New Energy Finance

Levelized cost of energy for utility-scale and small-scale solar

Historical

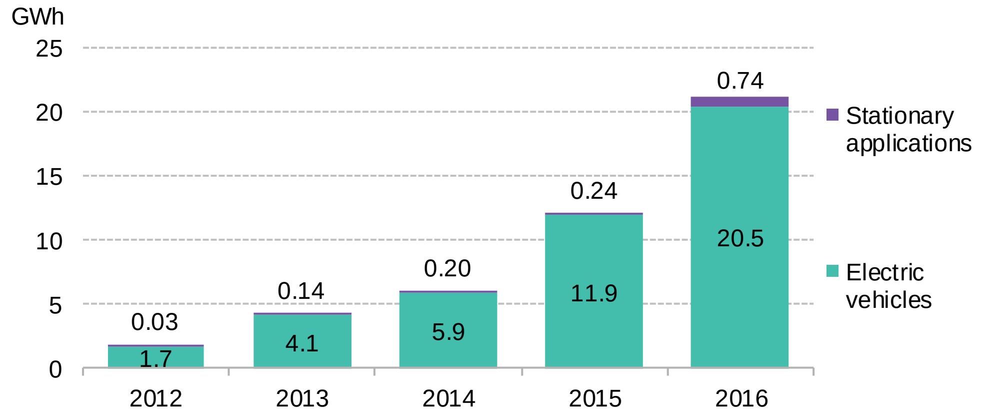
- PV module costs have been falling relentlessly, and will continue to do so.
  - From 1976 to 2016, module costs have gone from $82/W to $0.41/W (all in 2016 dollars). ***This represents a learning rate of 28%.*** There is a clear pathway to even lower prices through new wafering processes and tweaks to make cells more efficient.
- The cost decline of other components is harder to establish. Still, these have been getting steadily cheaper.
  - Conservative estimates for inverters suggest learning rates of 13%.
  - Installation costs have also dropped as new equipment is used to install modules.
- As the industry grows and matures, the cost of modules will keep on dropping. Examples of gains include:
  - **Thinner wafers**: this reduces the material needed per wafer, reducing cost
  - **Improved manufacturing efficiency**: this is focused primarily on reducing the energy intensity of making panels
  - **Higher module efficiency**: this improves the energy output of a module, delivering more power at the same price

Future

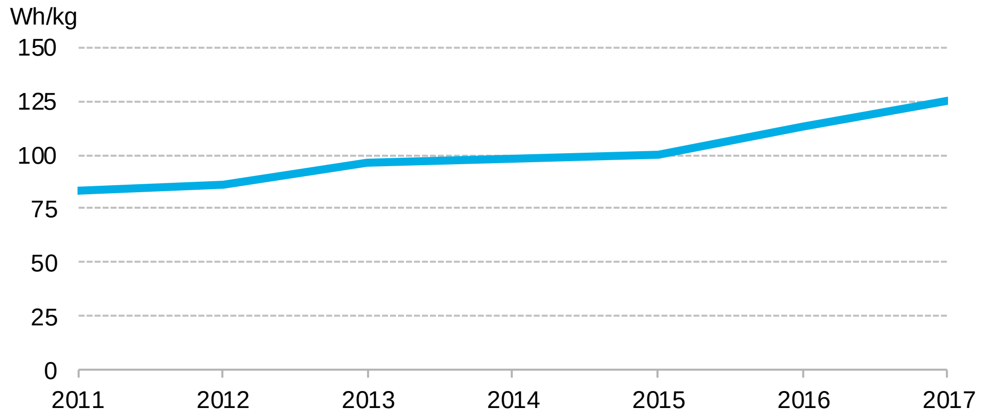
- As a result of these dynamics, ***utility-scale PV LCOEs in Europe drop from around $75/MWh in 2017 to $28/MWh in 2040***. The range of LCOEs for Europe captures differences across countries. These include:
  - **Different capacity factors** – lower in less sunny countries
  - **Different cost of capital** – higher in riskier countries
- The LCOE for small-scale PV follows the trend, but the important metric is its cost relative to retail prices. Retail prices or tariff structures may well adjust to reflect plentiful solar generation at midday, with lower prices then.
- This is underpinned by the fact that total capital expenditure for utility-scale and small-scale PV is expected to drop by 55% and 57% respectively over 2017-40. Most of the fall is explained by a 65% reduction in module costs. But other component costs also drop, by 41-55%.
  - Small-scale PV, which sits behind the meter, has a capex premium of 44% over utility-scale PV. This is primarily due to higher soft costs (financing, installation, etc) and fewer opportunities to benefit from economies of scale.

Costs for battery storage

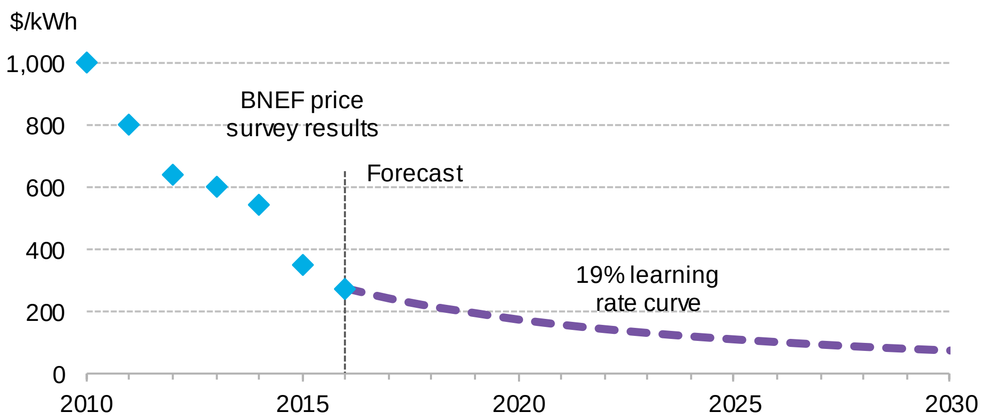
Lithium-ion battery global annual sales volume



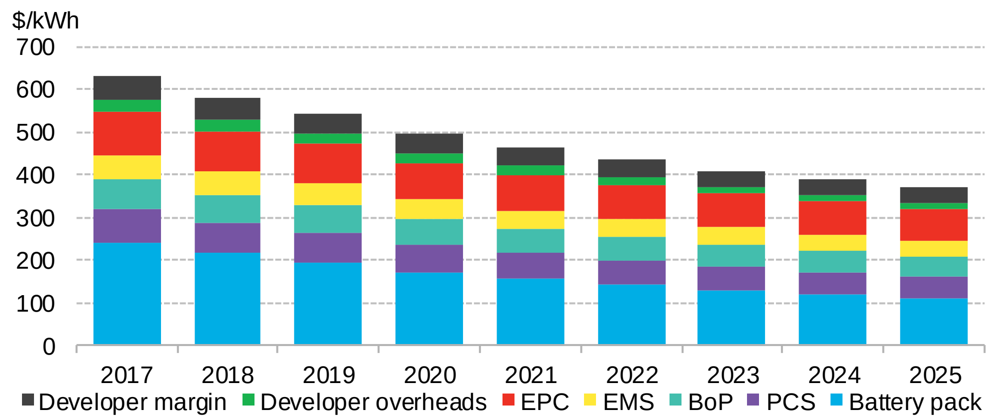
Industry average EV battery pack energy density



Lithium-ion battery price forecast



Forecast capital costs for an installed 1MW/1MWh project



Note: EPC is engineering, procurement, consulting, EMS is energy management systems, BoP is balance of plant, and PCS is power conversion system

Costs for battery storage

Historical

- Lithium-ion (li-ion) battery demand has boomed over 2012-17, with almost all battery packs going into electric vehicles (EVs). Batteries for energy storage have also started to pick-up, but the industry makes up less than 5% of demand.
- ***Costs for lithium-ion (li-ion) batteries have decreased by 73% over 2010-17***, with average costs going from around $1,000/kWh to $273/kWh. Since li-ion batteries make up a big part of an energy storage system cost – either for electric vehicle or stationary applications – total costs have also been coming down over the same period. The main cost drivers include:
  - **An uptick in demand**: increasing battery demand, especially from automakers, has boosted manufacturing expertise, driving costs down. Larger contracted order volumes also allow manufacturers to lower their price per unit.
  - **An oversupplied market**: cell manufacturers have increased production capacity, outpacing demand growth. An oversupply of batteries has forced producers to compete on price in order to win contracts.
  - **Technology improvements**: cell chemistries have increased the amount of energy that can be packed in a battery for the same volume and weight, reducing the use of expensive raw materials.

Future

- The battery makes up 38% of the cost of a stationary energy storage system, so developers need to take into account other costs, such as energy management and power conversion systems. The type of application can also have an impact on the cost per kWh of an energy storage system, with those geared towards power being significantly more expensive.
- ***We expect a 42% decrease over 2017-25 in the average cost of a 1MW/1MWh fully installed system***, going from $631/kWh to $369/kWh. This is because of:
  - **Battery costs**: at a learning rate of 19%, li-ion battery costs drop 73% over 2017-30. This accounts for 55% of cost reductions in energy storage systems.
  - **Other components**: other systems, such as for energy management and power conversion, see costs go down by 37% as the technology gets better and experience grows.
  - **Installation**: as more energy storage systems are deployed, developer experience and competition drives construction costs down.

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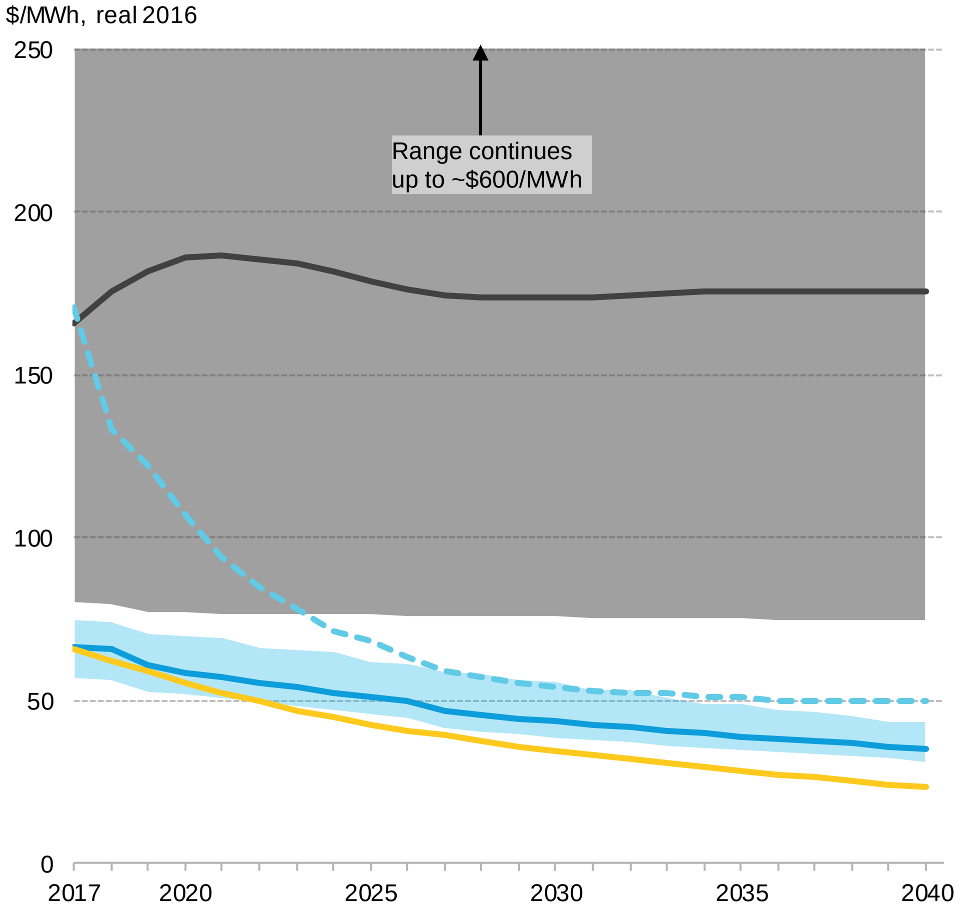
Cost tipping points

When do renewables become cheapest

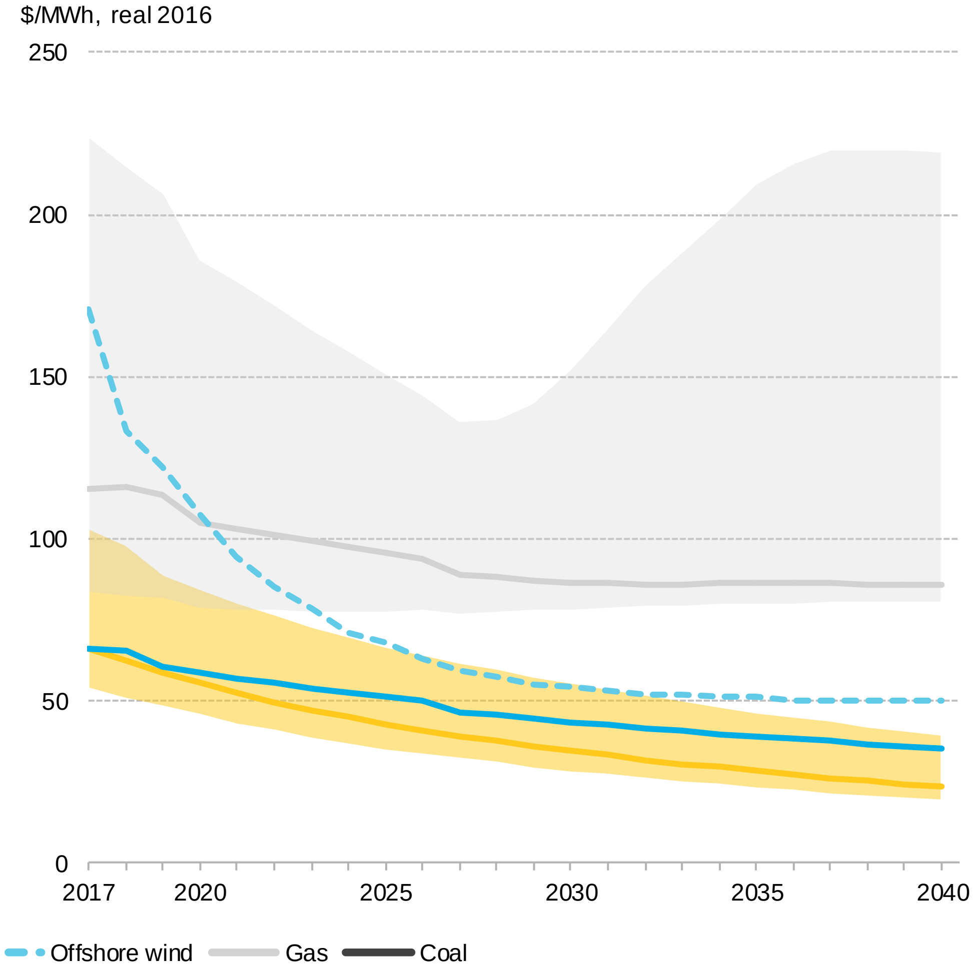
Tipping point 1: when new-build renewables beat new-build gas and coal

LCOE forecast range for new-build coal, onshore and offshore wind, and utility-scale PV in Europe



Source: Bloomberg New Energy Finance

LCOE forecast range for new-build gas, onshore and offshore wind, and utility-scale PV in Europe



Source: Bloomberg New Energy Finance

Tipping point 1: when new-build renewables beat new-build gas and coal

Tipping points

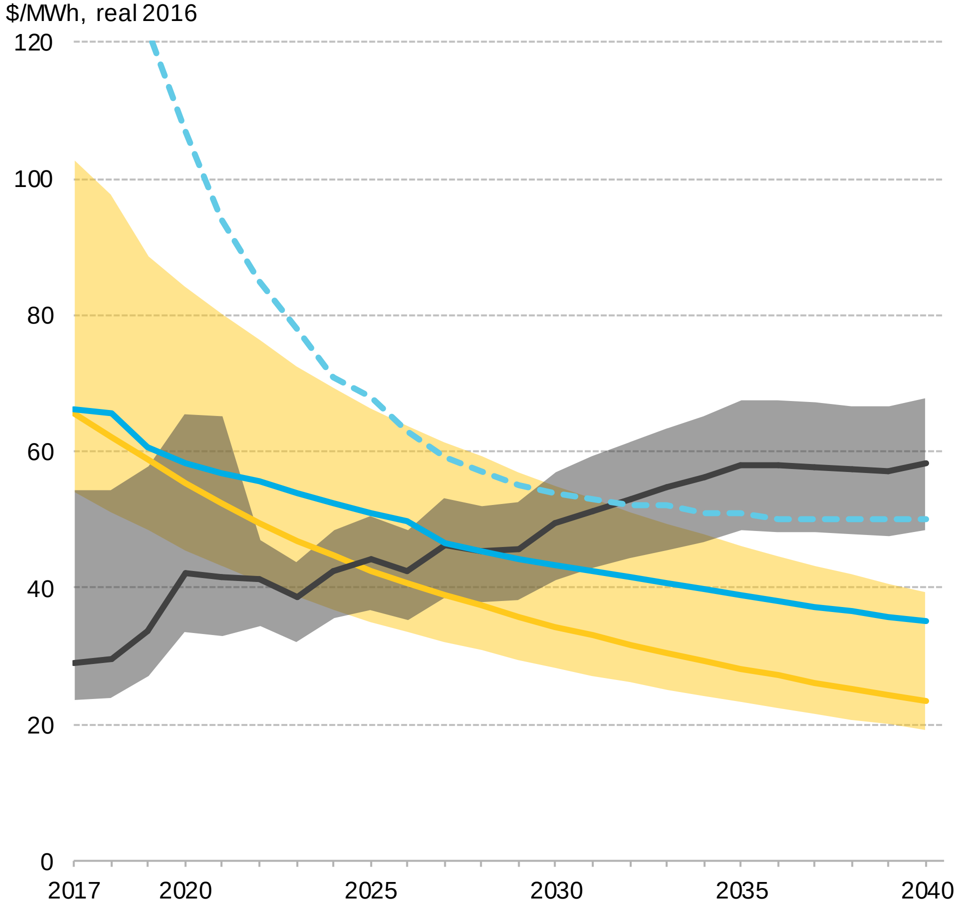
- The relative cost of new wind and solar and other new capacity is a key metric driving deployment when additional energy sources are required.
- In Europe, like most of the world, coal and gas have been traditionally the preferred technologies for most new build.
- The LCOE for new coal and gas fluctuates over time. Unlike wind and solar costs, which are primarily driven by improvements in technology, coal and gas LCOEs are determined by:
  - **Commodity prices**: the price of coal, gas and carbon all affect the generation costs of these technologies. Increasing gas prices are putting upward pressure on the LCOE of gas, while coal is significantly affected by rising carbon costs.
  - **Capacity factors**: the less these plants run, the higher their LCOEs, as they need to recover fixed and capital costs over smaller sales volumes. Both gas and coal plants see their capacity factors reduced as renewable penetration increases, creating a vicious circle.

Implications

- As a result of these dynamics, ***power from new onshore wind and solar is already cheaper than from new gas*** across Europe, with offshore wind also expected to beat gas by the early 2020s.
- This is not a major driver of wind and solar additions in Europe, however. With electricity demand on the continent expanding only 2% over 2017-40, the need for new build is very limited, so wind and solar will be economically built only when other plants retire.
- Renewables are also cheaper than new coal in most of Europe. This underscores the dominance of wind and solar over the dirtiest fuels, but the comparison is of little practical importance. Regulatory uncertainty around coal – some countries like the U.K. are planning a coal phase-out, with others strongly considering it – makes it unlikely that new coal plants would get built, even if their relative costs were below those of wind and solar.

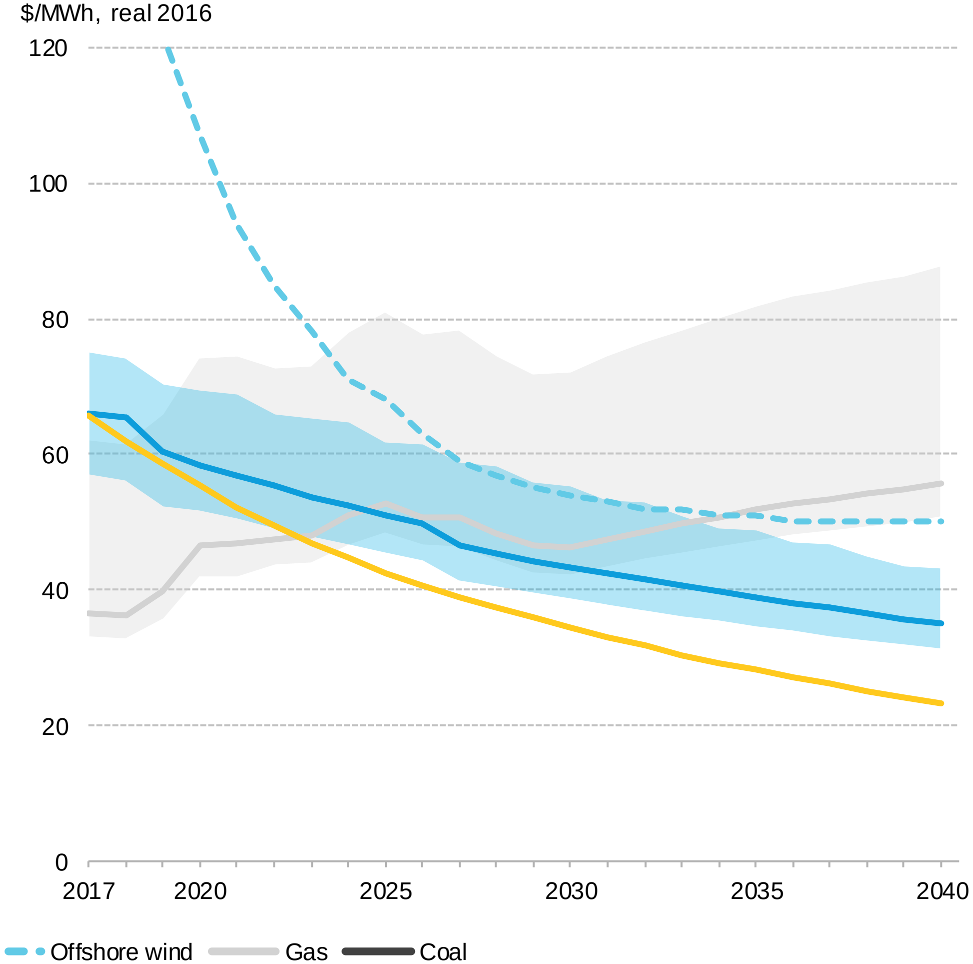
Tipping point 2: when new-build renewables beat existing gas and coal

LCOE forecast for wind and PV, and generation cost range of existing coal in Europe



Source: Bloomberg New Energy Finance

LCOE forecast for wind and PV, and generation cost range of existing gas in Europe



Source: Bloomberg New Energy Finance

Tipping point 2: when new-build renewables beat existing gas and coal

Tipping points

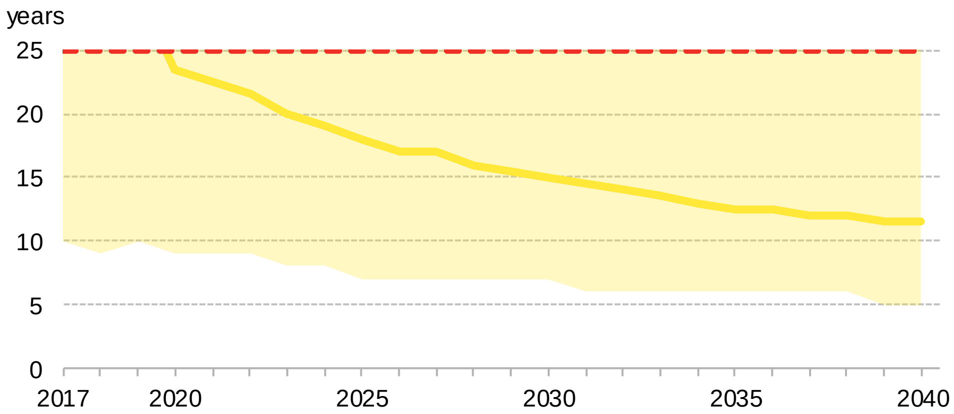
- The difference between the levelised cost of energy (LCOE) produced by new wind and solar and the operating cost of existing capacity is another key metric.
  - The most important cost crossover points renewables need to reach are those with existing coal and gas plants.
- The short-run marginal cost of a generator (SRMC) is defined as the price needed by it to recoup all costs directly incurred from the production of a unit of energy (variable costs). In the case of coal and gas plants, the SRMC is driven by fuel and emission costs.
- Since each gas or coal plant is built with different specifications, the SRMC for these two technologies is best represented by a range.
  - **Plant efficiency** is key in determining the SRMC. All else being equal a gas plant with low efficiency will have a higher SRMC than one with high efficiency.
  - **Age** is an important determinant of efficiency. Older plants will have lower efficiencies because they rely on less modern technologies, and because of component wear and tear.

Implications

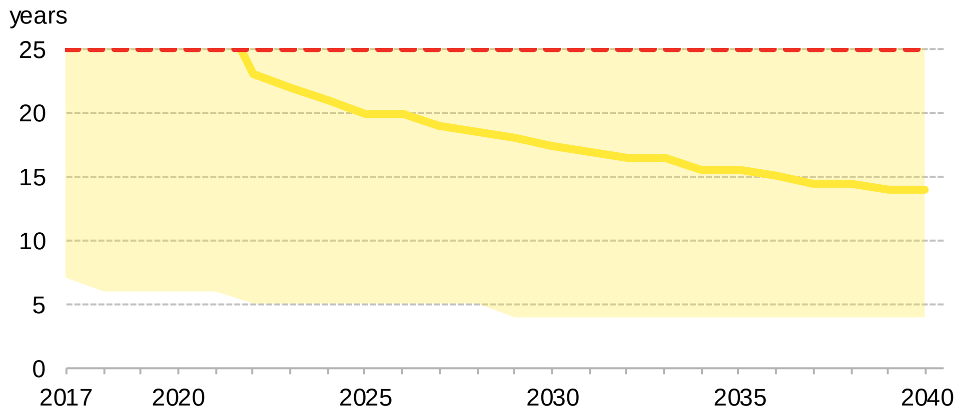
- When the LCOE of wind and solar drops below the SRMC of coal and gas, ***it becomes cheaper to replace these fossil fuels with renewables for energy needs*** – though not necessarily for capacity.
- This dynamic can be delayed by:
  - **Low demand growth** and oversupply, reducing the need to replace retiring coal or gas capacity.
  - **Need to meet peak demand**, requiring the system to keep some coal and gas plants online to supply energy during hours of low renewable output.
- The SRMC of coal and gas is expected to keep rising. Increasing gas prices drive up the cost of gas plants. Carbon pushes coal generation costs up.
- As a result of these dynamics:
  - **Today**, the best new solar and wind projects already produce energy cheaper than produced by the oldest coal and gas plants.
  - **By the mid-2020s**, energy from new wind and solar plants becomes cheaper than the that from the average European gas plant.
  - **By 2030**, energy from new wind and solar is also cheaper than from the average European coal plant.
  - **By 2040**, all new wind and solar projects produce cheaper energy than produced by any existing fossil fuel plants.

Tipping point 3: when small-scale PV becomes cheaper than the grid

Payback period for residential small-scale PV systems in Europe

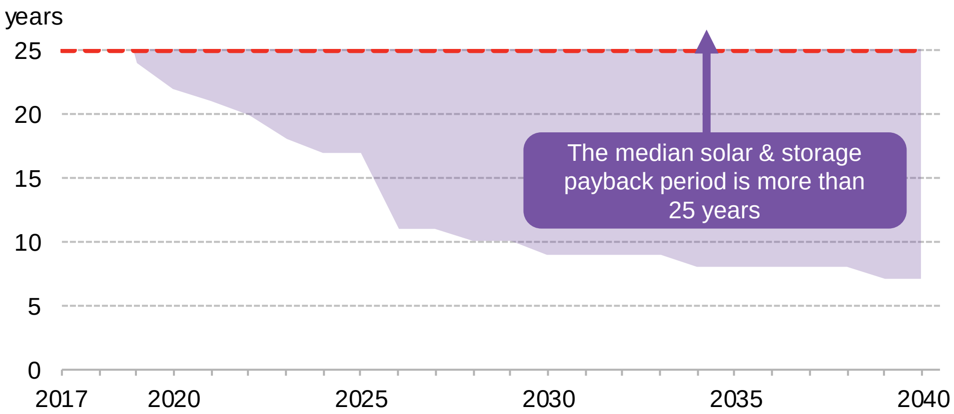


Payback period for commercial small-scale PV systems in Europe

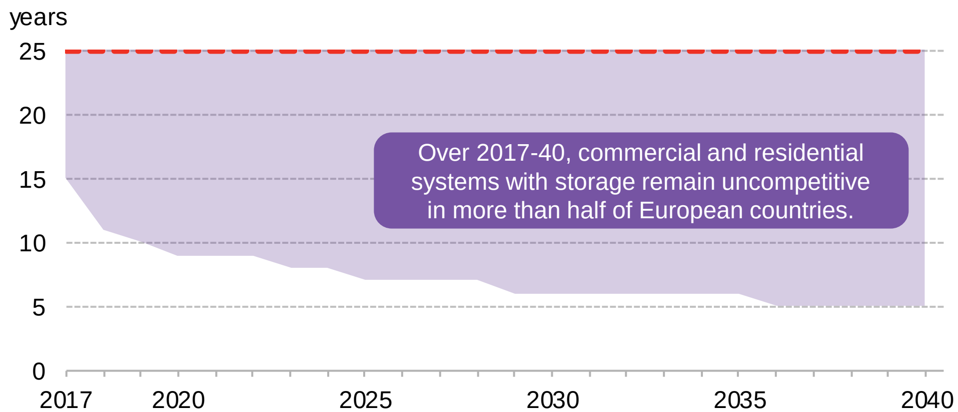


Min-max range for solar only
Min-max range for solar & storage
Median for solar only
Technical lifetime

Payback period for residential small-scale PV systems with storage in Europe



Payback period for commercial small-scale PV systems with storage in Europe



Tipping point 3: when small-scale PV becomes cheaper than the grid

Tipping points

- The most important tipping point for a small-scale PV system is whether it repays itself over its technical lifetime – with or without a battery**.** If revenues do not cover costs, then the investment never happens.
- Small-scale PV systems are divided between *residential* and *commercial* consumers. Two metrics separate them:
  - **Retail prices**: commercial and residential customers pay different electricity tariffs across all of Europe.
  - **Self-consumption rate**: commercial customers have a higher rate than residential ones, as their electricity demand coincides better with solar output.
- There are multiple potential revenue sources for rooftop PV:
  - **Avoided retail costs**: by using the electricity from their own system, consumers are able to reduce part of their retail bills.
  - **Grid feed-in payments**: some countries pay owners to feed excess electricity back into the grid.
  - **Providing grid services:** systems that include batteries might be able to capture value by offering services back to the grid. We do not include this in our modeling.
- A few other factors can affect project economics and the decision to invest in a system, or not:
  - **Self-consumption rate**: how much of the electricity generated coincides with consumption. A battery can increase this, but at an added cost.
  - **Insolation**: in countries with more sun, rooftop system economics improve.
  - **Space availability**: this can limit investment, even if the economics are favorable.
  - **Policy**: ownership rights for rooftops can reduce incentives for installing PV systems – an owner renting out a property might not want to install a system.

Implications

- By 2017, ***systems without a battery are already cheaper than grid electricity in some European countries***.
  - Payback periods can be as low as 10 years for residential, and seven years for commercial systems.
  - Residential systems become economical in half of Europe by 2020, and commercial ones by 2022.
  - By 2040, payback periods halve across Europe.
- Systems with a battery take longer to become competitive due to higher capital costs, not taking into account potential additional revenue streams.
  - In 2017, the only systems that can repay their costs are commercial installations in a few European countries.
  - Residential systems start to become economical in 2019 in some European countries.
  - Despite big cost reductions to 2040, solar-battery systems remain uncompetitive across most of Europe.

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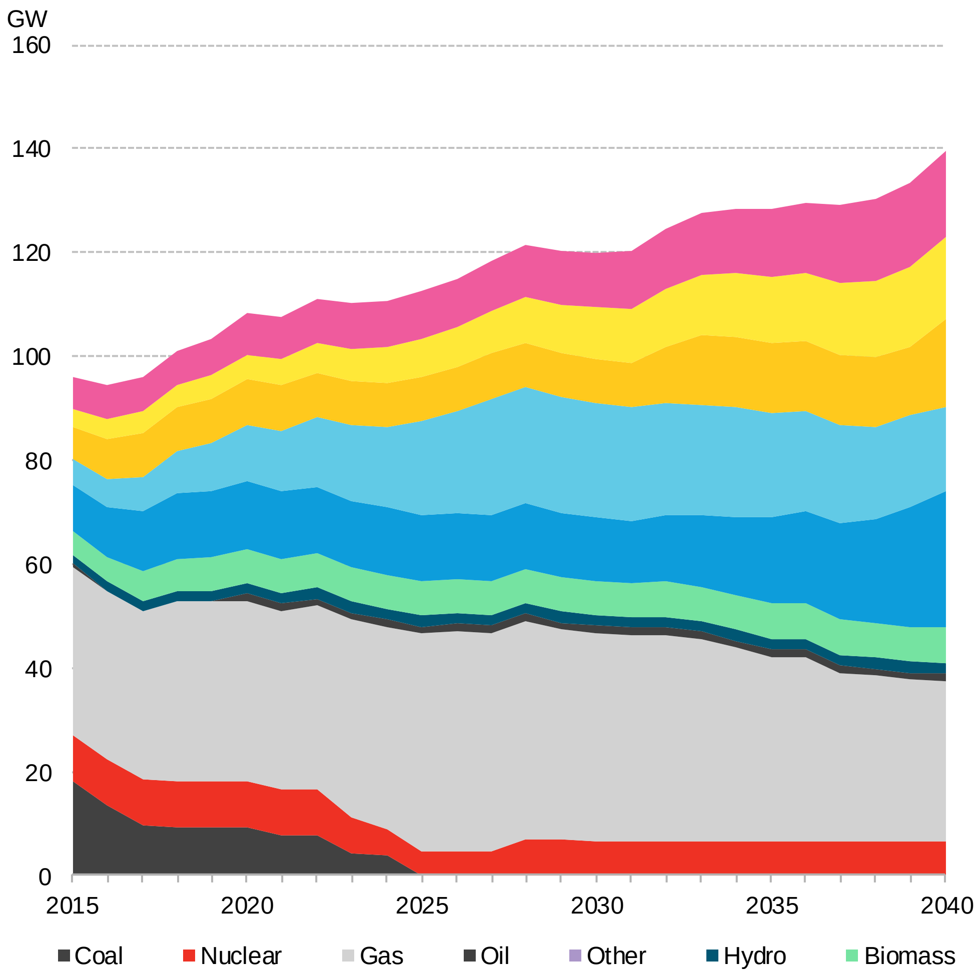
Renewables deployment

Dynamics determining the build-out of wind and solar capacity

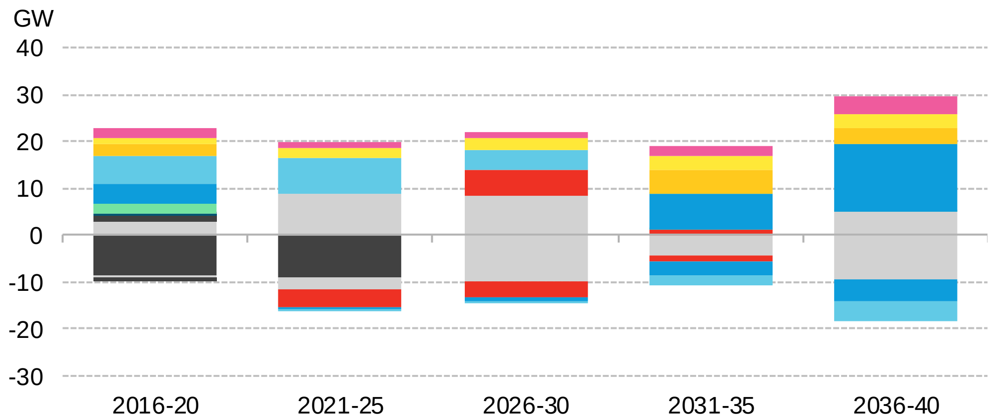
United Kingdom

Cumulative installed capacity



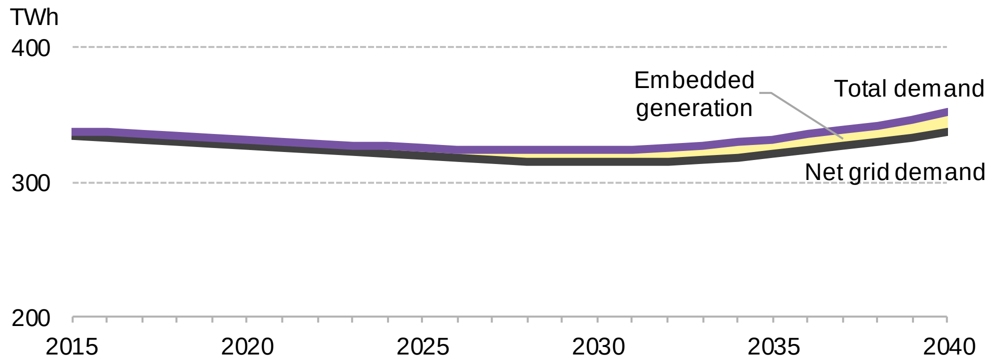
Source: Bloomberg New Energy Finance

Additions and retirements



Source: Bloomberg New Energy Finance

Electricity demand



Source: Bloomberg New Energy Finance

United Kingdom

United Kingdom dynamics

- In the U.K., economics strongly favor onshore wind. The technology reaches tipping point 2 in the 2030s as power from new wind farms becomes cheaper than that from existing gas.
- But market dynamics beyond economic tipping points also strongly influence the country's future energy mix and can slow the uptake of onshore wind and solar even as these technologies become the most economic sources of power. These dynamics include:
  - **Two distinct demand periods**: U.K. electricity demand shrinks by 4% over 2017-30, to 324TWh. Improving economic efficiency and de-industrialization drive the drop. A strong pick-up in electric vehicles after that drives demand up to 352TWh by 2040, for an overall 2017-40 demand growth of 4%.
  - **Capacity market**: the U.K. has a mechanism that pays generators – new and existing – to provide the system with back-up capacity. This mechanism strongly favors gas, while excluding wind and solar.
  - **Offshore wind subsidies**: auctions for offshore wind subsidies mean that technology additions will be driven by policy until the mid-2020s. As we have no policy visibility after that, we assume the last policy-driven additions come online in 2026.
  - **Low insolation**: a poor resource significantly hampers economics for solar, both small-scale and large-scale.

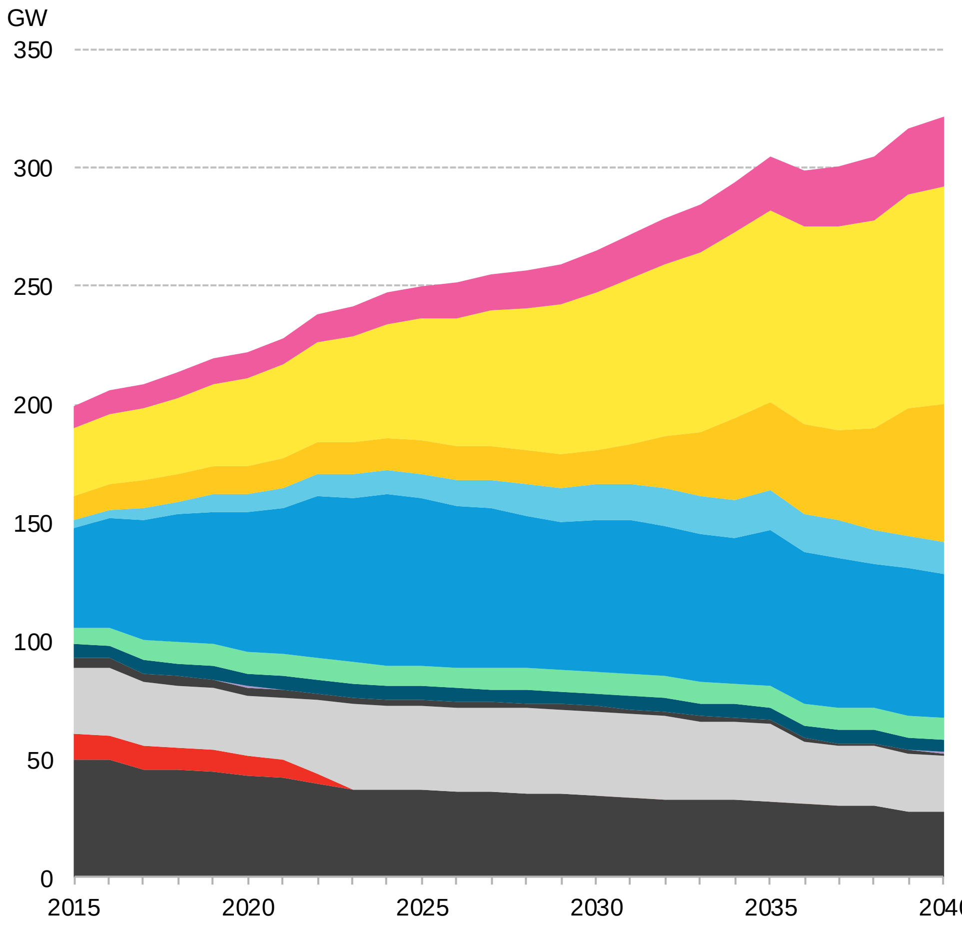
Capacity evolution

- The combination of tipping points and these market-specific considerations means that:
  - **Offshore wind grows until subsidies end**. A series of auction rounds for offshore wind subsidies bring another 15GW of capacity online by 2026, leaving little room for onshore wind. After that, additions stop, and capacity shrinks to 16GW in 2040, as some older farms reach the end of their technical lifetime.
  - **Gas dominates as coal capacity is closed**. The U.K. has announced – but not yet legislated – a mandatory coal phase-out by 2025. The space left by coal is forecast to be filled by gas plants. Capacity grows to 42GW by 2028, as retiring nuclear and coal is replaced with gas to maintain necessary capacity levels. After that, retiring gas plants at the end of their lifetime are replaced by batteries and demand response, with capacity shrinking back to 31GW in 2040.
  - **Onshore wind grows as offshore wind and gas shrink**. Onshore wind capacity stays flat at 13GW over 2017-30. After that, and partly thanks to growing electricity demand, onshore wind grows to 26GW by 2040. This pushes out some gas capacity and also replaces retiring offshore wind.
  - **Solar is split evenly between small and large systems**. Solar capacity triples over 2017-40, to 33GW, with half being utility-scale installations. The other half is small-scale systems, which the UK deploys at an average of 0.5GW per year over 2017-40. After 2030, an increasing number of these systems come with batteries, reaching a cumulative 2GW by 2040.

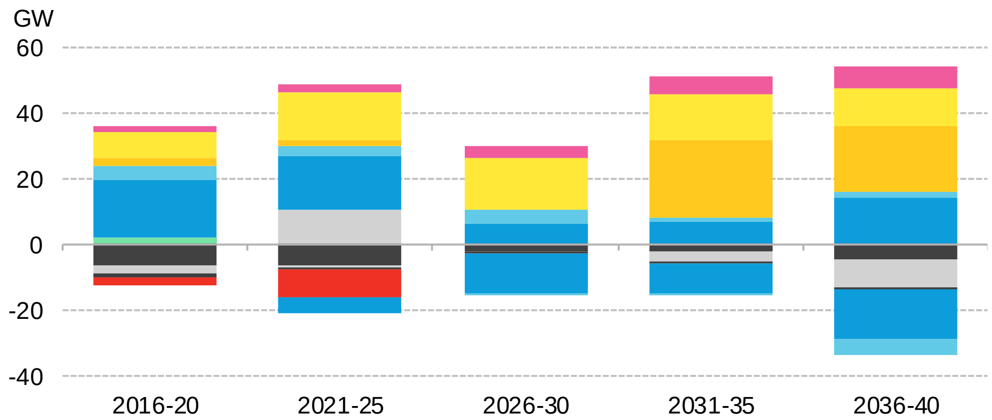
Renewables deployment

Germany

Cumulative installed capacity

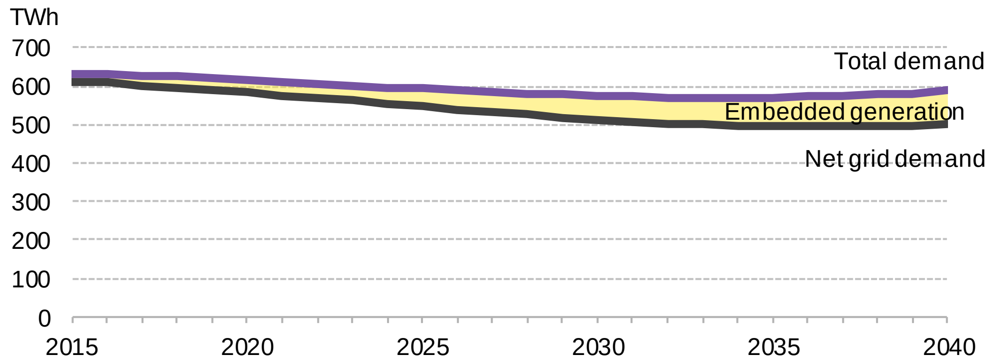


Additions and retirements



Source: Bloomberg New Energy Finance

Electricity demand



Coal · Nuclear · Gas · Oil · Other · Hydro · Biomass · Onshore wind · Offshore wind · Utility-scale PV · Small-scale PV · Flex

Source: Bloomberg New Energy Finance

Source: Bloomberg New Energy Finance

Germany

Germany dynamics

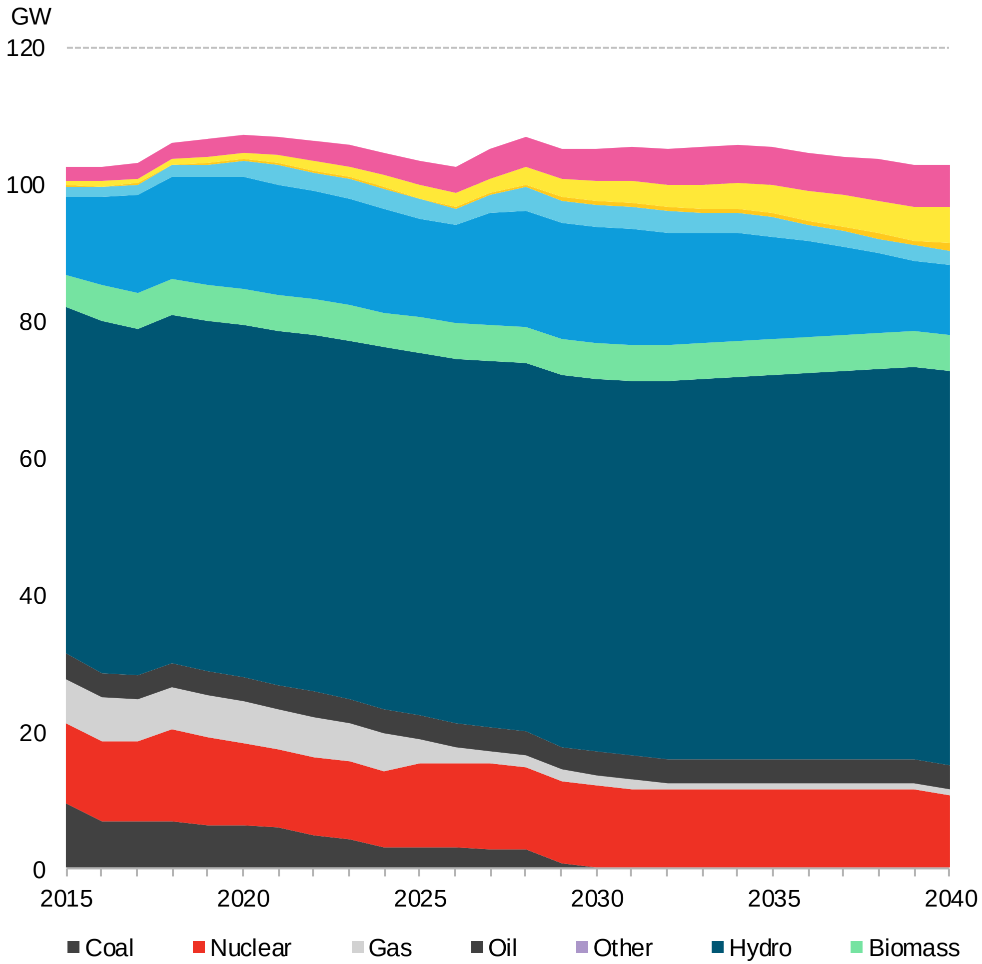
- In Germany, solar economics dominate, with small-scale PV in some cases having already reached tipping point 3. Utility-scale PV reaches tipping point 2 in the late 2020s as power from new installations becomes cheaper than from existing gas.
- However, the German power system has a few key dynamics that affect the evolution of installed capacity over 2017-40, in some cases distorting some of the tipping point effects.
  - **Shrinking demand**: total electricity demand in Germany shrinks by 10% over 2017-35. Increased energy efficiency, and de-industrialization of the economy, drive this sharp decline. Over 2035-40, electric vehicle charging picks up, and total electricity demand grows by 3%, to 589TWh.
  - **Small-scale PV economics**: Germany has favorable small-scale PV economics, and a large market eager to adopt the technology. Growth in such systems crowds out other technologies, and reduces grid-connected demand.
  - **Cheap coal**: a large, highly efficient lignite fleet provides cheap electricity that is hard to displace, delaying tipping point 2 vis-à-vis coal.
  - **Retiring onshore wind**: by the mid-2020s, the first wind farms start retiring as they reach their technical lifetimes. This creates space for new build, mostly taken up by cheap solar.

Capacity evolution

- The combination of tipping points and these market-specific considerations means that:
  - **Small-scale PV drives additions.** Over 2017-40, German small-scale PV capacity triples, to 93GW. By the mid-2020s, around 1GW of batteries are installed along with such systems, that capacity growing to 6GW in 2035 and 11GW in 2040.
  - **Utility-scale PV is late to grow.** Despite being the cheapest technology by the mid-2020s, capacity over 2017-30 only grows by 2GW as small-scale PV dominates additions and little residual demand is left. Over 2030-40, however, growing demand from electric vehicles and retiring wind causes capacity to quadruple.
  - **Solar pushes out fossil capacity after 2035.** The addition of new sources of flexible capacity such as storage, demand response and dynamically-charging electric vehicles reduces the firm capacity requirements after 2035. This allows utility-scale solar to squeeze out some coal and gas capacity.
  - **Onshore wind stagnates after 2025.** The technology enjoys a short period of economic dominance, over 2017-25, with capacity growing 40%. Over 2025-40, capacity shrinks by 10GW. Some retiring onshore wind is replaced by new turbines with higher energy yields, with solar making up the rest.
  - **Fossil fuel capacity is on the decline.** Coal and gas capacity shrinks by 28% over 2017-40. Nonetheless, a combined 50GW of coal and gas plants are still needed in 2040, in order to provide back-up for wind and solar.

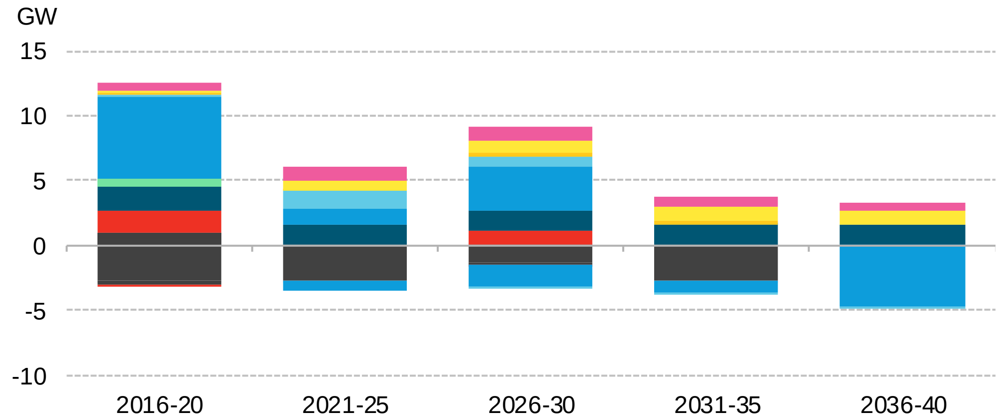
Nordics

Cumulative installed capacity



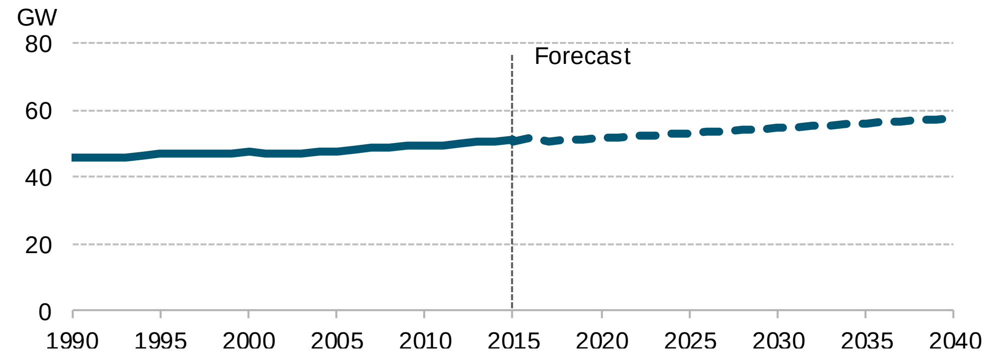
Source: Bloomberg New Energy Finance

Additions and retirements



Source: Bloomberg New Energy Finance

Historical and forecast Nordic hydro capacity



Source: Bloomberg New Energy Finance

Nordics

Nordics dynamics

- A massive hydro fleet continues to shape the Nordic power market. Beyond that, there is little space for other technologies and little relevance to economic tipping points. Only tipping point 3 is relevant, with small-scale solar starting be able to compete with retail prices in some parts of the region in the 2020s.
  - **A hydro-dominated market**: The Nordic region has the largest proportion of hydro capacity in its mix. Norway and Sweden account for almost all of it. These two countries have developed such projects for over a century, and continue building some small-scale facilities, as well as improving old ones.
  - **Very low insolation**: Stretching all the way to the Arctic, the Nordic region has a very low solar resource. In the winter, when power demand is highest, there are periods when the sun is up for just a few hours a day – and not at all in those places north of the Arctic Circle.
  - **Nuclear provides round-the-clock output**: Concentrated in Sweden and Finland, Nordic nuclear capacity provides steady carbon-free power. Finland is still building new nuclear plants.
  - **Subsidy-driven wind**: Wind capacity, onshore and offshore, is concentrated in Denmark and Sweden. Subsidies have so far driven additions in these two countries.

Capacity evolution

- These dynamics mean that in the Nordics:
  - **Hydro continues to lead the way.** Hydro capacity in the Nordics makes up 50% of the total in 2017. That proportion is set to grow to 56% in 2040, as the region increases hydro capacity by 8GW. While there are little opportunities for new hydro projects, regular maintenance and upgrades at existing stations are what have been, and will keep on, driving up capacity.
  - **Small-scale PV drives solar.** Solar capacity in the Nordic region grows from 1GW in 2017 to 6GW in 2040. Additions come almost exclusively from small-scale systems, as favorable grid economics drive limited adoption. Utility-scale solar struggles to make an economic case due to its low yield.
  - **Wind capacity grows minimally once subsidies end.** Subsidies drive 7GW of onshore wind additions, and 1GW of offshore wind, over 2016-25. After that, additions slow dramatically, as hydro and nuclear leave little space. Over 2026-40, some 3GW of onshore wind are built as 8GW are retired, while 1GW of offshore wind is built in 2027.
  - **Coal is driven out by 2030**: The 7GW of coal capacity online in 2017 shuts down due to poor economics by 2030, mainly replaced by hydro.

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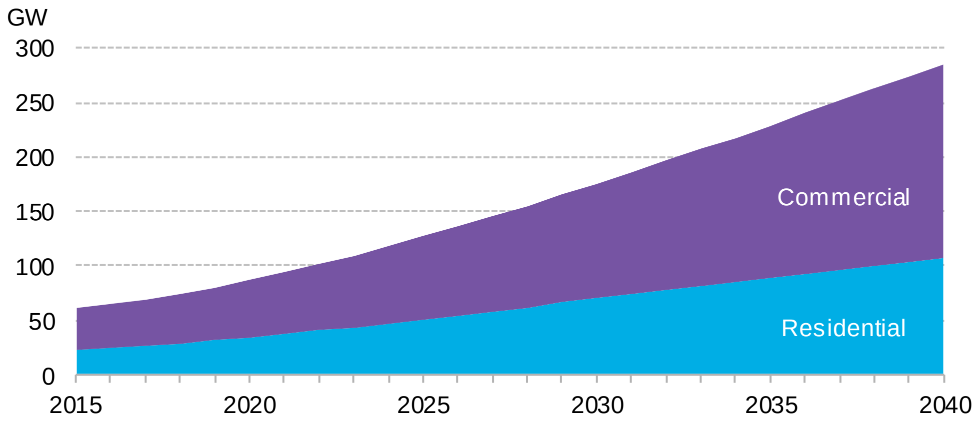
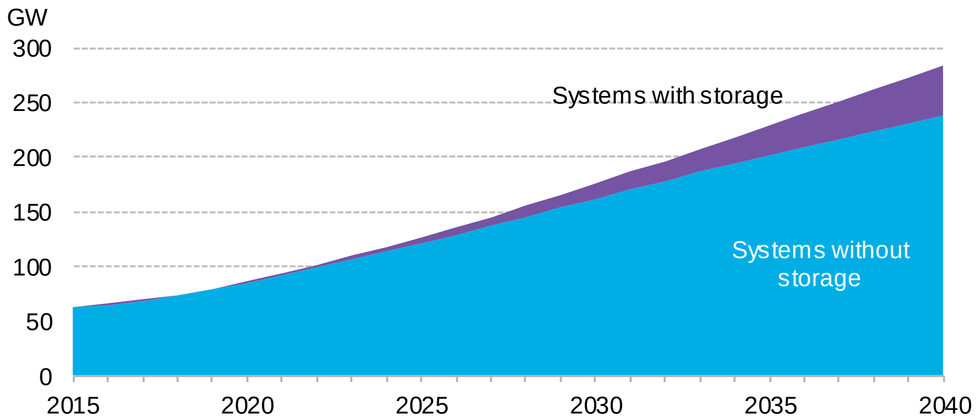
Modeling assumptions

Deployment of small-scale PV and storage, and flexible capacity

European cumulative small-scale PV capacity

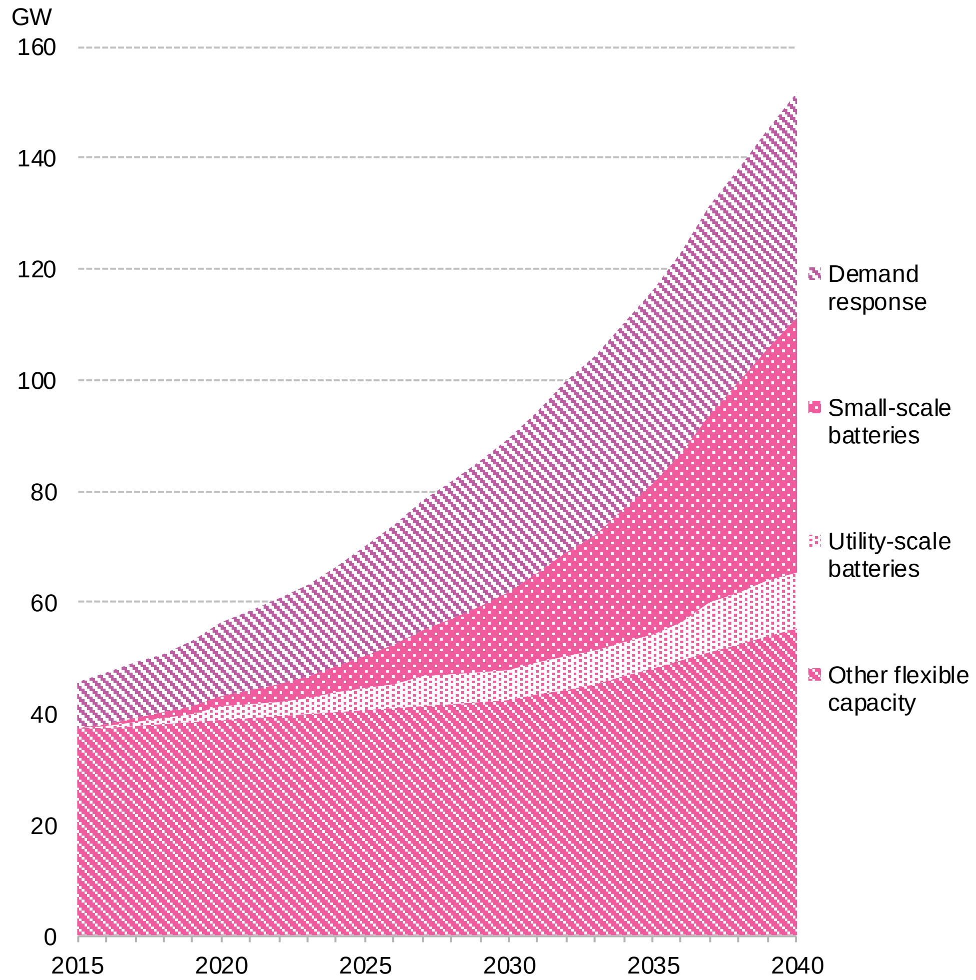


European cumulative small-scale PV capacity



Source: Bloomberg New Energy Finance

European cumulative flexible installed capacity



Source: Bloomberg New Energy Finance

Deployment of small-scale PV and flexible capacity

Small-scale PV and small-scale storage

- The growth of small-scale PV and storage to 2040 will be driven by millions of individual homes and businesses taking economic decisions to invest in new technology. We model this using a consumer diffusion approach, based on the relative economics of retail electricity versus small-scale PV with/without storage.
- European small-scale PV (SSPV) capacity will increase fourfold to 284GW over 2017-40.
  - Adoption in our modeling is driven by the LCOE of SSPV versus the variable component of the retail price of electricity, and the coincidence of personal electricity consumption with daytime solar generation.
- Commercial small-scale solar represents a bigger market, consistently making up around 60% of total SSPV capacity.
  - As business hours coincide with solar generation, the value of the energy from an SSPV system is higher for commercial installations than for residential ones.
- By 2040, around 46GW of small-scale PV systems will include a battery.
  - As batteries become cheaper, residential systems will increasingly use them to shift solar energy to fit their consumption patterns.
  - Potential additional revenue captured by these batteries (e.g. from providing ancillary services) is not included in our modeling. These benefits will make batteries more attractive and thus could lead to faster uptake.

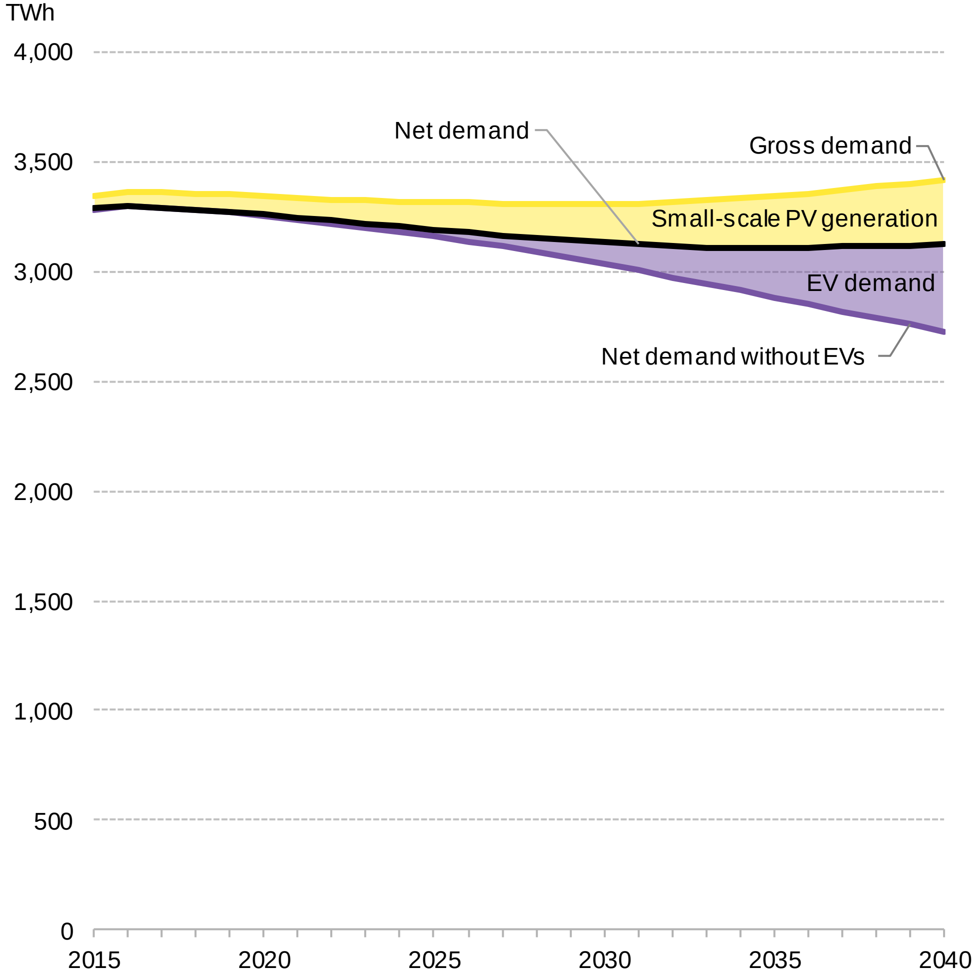
Flexible capacity

- Flexible capacity refers to technologies used primarily to meet peak demand, such as battery storage, demand response and pumped hydro.
- European flexible capacity increases threefold to 152GW over 2017-40.
  - Most of the growth comes from small-scale batteries. By 2040, Europe has 46GW of such batteries, installed alongside small-scale PV systems.
- Demand response and utility-scale batteries are increasingly installed as European power systems become peakier.
  - From 2017-40, utility-scale battery capacity grows by 9GW, while demand response capacity increases by 31GW.
  - Utility-scale batteries require a high initial investment but then are inexpensive to operate. Demand response has a very low initial investment but can have a high utilization (opportunity) cost.
- Europe also has around 38GW of other flexible capacity in 2017. This is mostly pumped-hydro storage.

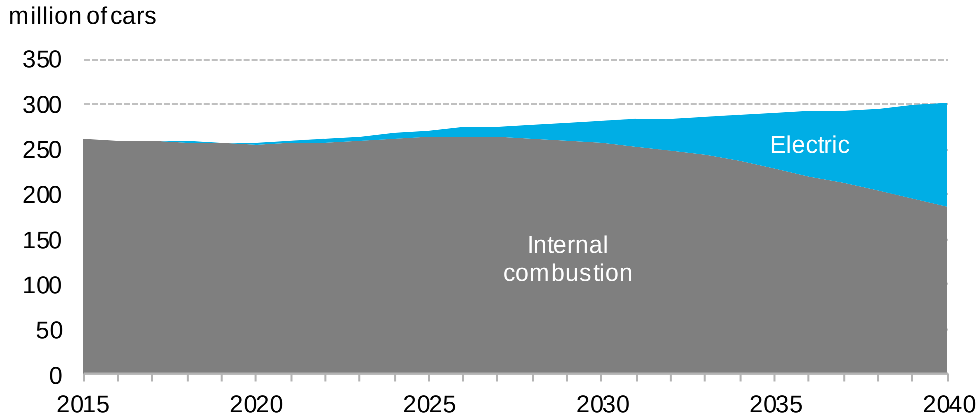
Modeling assumptions

Electric vehicles and the evolution of electricity demand

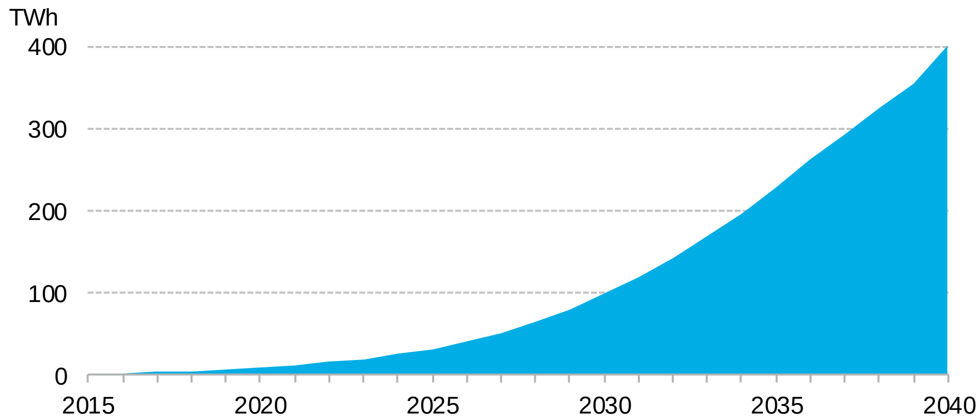
Total electricity demand



Cumulative light-duty vehicles on the road in Europe



Electricity demand from electric vehicles in Europe



Electric vehicles and the evolution of electricity demand

Total electricity demand

- Gross electricity demand in Europe grows 2% in total from 2017 to 2040, reaching 3,416TWh. Two dynamics pull demand in opposite directions:
  - Underlying electricity demand shrinks by 10% as the European economy de-industrializes, and energy efficiency improves.
  - Electricity demand from electric vehicles grows from close to zero in 2017 to around 12% of gross demand in 2040, as transport electrifies.
- Net electricity demand in Europe shrinks by 5% over 2017-40. As residential and commercial consumers install close to 300GW of rooftop PV, distributed generation reduces grid-connected demand by 9% in 2040.
  - This type of demand presents both a challenge and an opportunity:
    - **Challenge**: grid-connected generation assets will have to compete for a shrinking pie
    - **Opportunity**: managing and monetizing this source of generation creates new revenue streams.

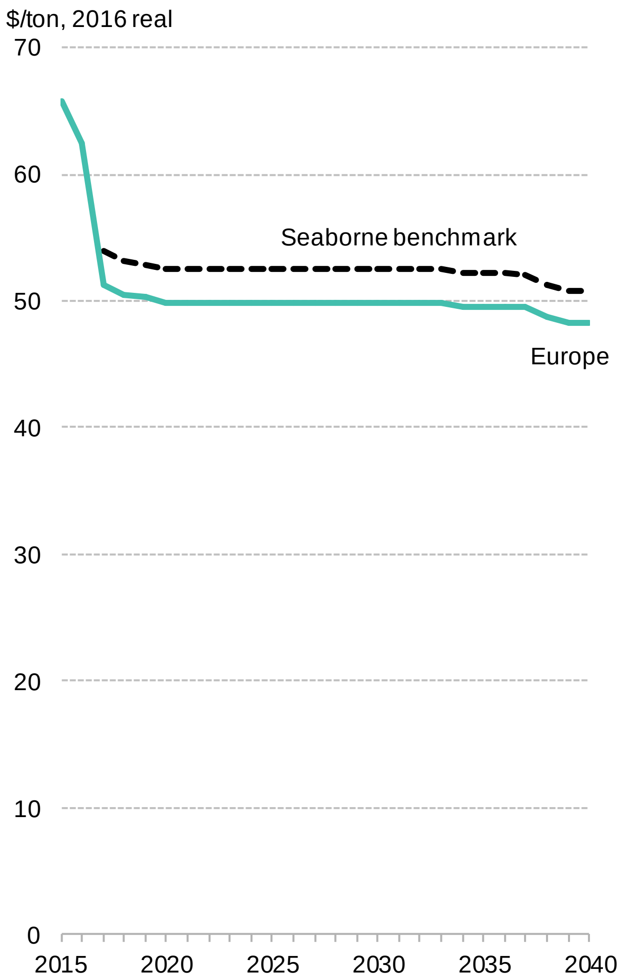
Electricity demand from electric vehicles

- There are currently around 700,000 EVs on the roads of Europe. By 2040, the European EV fleet will grow to 114 million cars, making up 38% of all light-duty vehicles.
- The adoption of EVs is primarily driven by their upfront cost in comparison to that of internal combustion engine vehicles (ICEs).
  - By the mid to late 2020s, the upfront cost of an EV reaches a parity point with that of equivalent ICEs in all segments.
- As the European EV fleet grows, EV-related electricity demand also grows, from around 3TWh in 2017 to 401TWh in 2040.

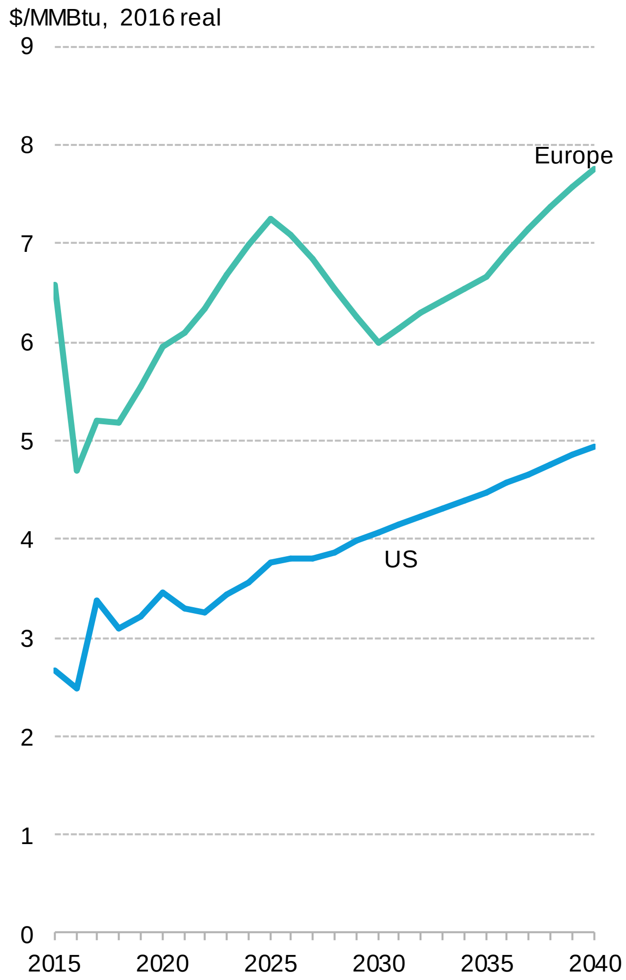
Modeling assumptions

Commodity price forecasts

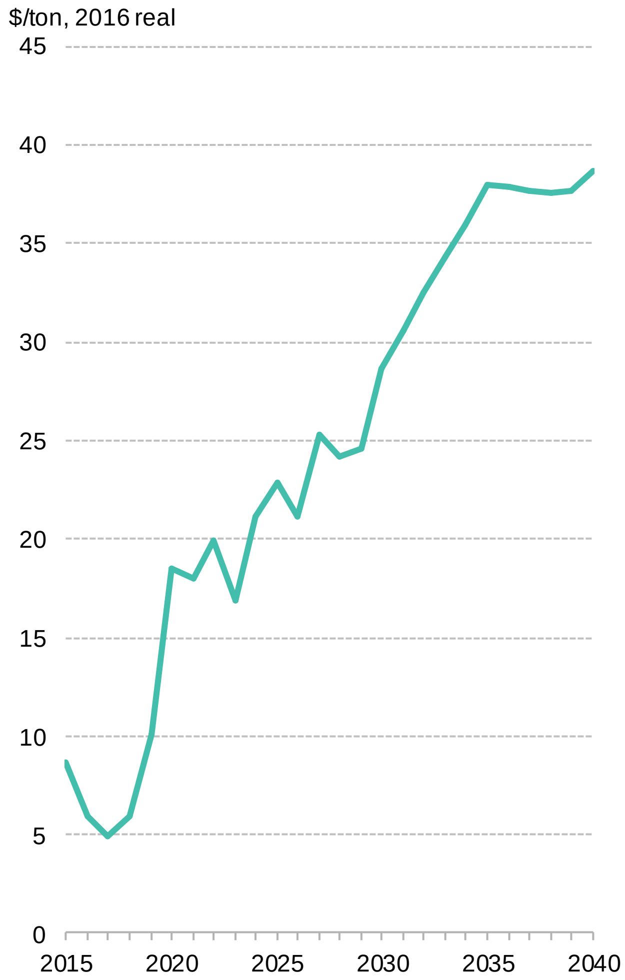
European coal price



European gas price



European carbon price



Commodity price forecasts

European coal price

- Our benchmark coal price forecast falls below $60/t in real terms, and then remains flat at around $53/t to 2040.
  - Lower transportation costs to Europe mean that coal on the continent trades at a consistent 5% discount to the seaborne benchmark.
- Global seaborne coal demand peaked at around 800Mt in 2013. We expect that it will not reach this peak again and will instead fall to 550Mt in 2040.
- Within this demand range, the supply curve indicates that Australian, Colombian and Indonesian supply are on the margin, at a price of around $50-55/t.

European gas price

- We assume European gas prices become increasingly linked to U.S. gas prices as global LNG trade picks up.
  - Increased demand for U.S. gas pushes its price up from $3/MMBtu in 2017 to $5/MMBtu in 2040.
- The European gas price forecast is volatile over the medium term. Russia's attempts to retain market share lead to price volatility.
- Over the medium to long term, we expect European gas prices to start following global LNG prices.

European carbon price

- We forecast that European carbon prices will go from $5/t in 2017 to $39/t in 2040.
- We expect the current oversupply in the European carbon market will be addressed by the Market Stability Reserve (MSR). This starts in 2019, making supply more flexible.
  - As a result of this, forecast prices increase to around $19/t in 2020.
- Over the medium term, we expect the price to remain bellow $25/t.
  - Falling wind and solar costs reduce the carbon price needed to achieve the de-carbonization target.
- Over the long term, European carbon prices increase to $39/t by 2040. As relatively cheaper de-carbonization options are exhausted, a higher carbon price is needed to keep emissions going down.

U.K.: overview of scenarios and issues

Analysis of a high-renewables power system in the U.K.

Overview of issues

This section summarizes some of the core issues that arise in a high-wind and high-solar future for the U.K.

We explore four main issues:

1. Wind and solar energy exceeds demand at times

- Wind and solar generation respond to weather conditions that are independent of demand. As a result, there is a mismatch between variable renewable generation and demand.
- Initially, wind and solar generation exceeds demand when periods of high output coincide with periods of low demand (e.g. overnight or during a sunny weekend).
- As more wind and solar capacity comes online, variable renewable generation exceeds demand more frequently, sometimes even during periods of high demand.

2. Significant back-up capacity is still required

- Regardless of the level of wind and solar capacity installed, there will still be moments with very low to no wind/solar output.
- Spikes in demand that coincide with a still, cloudy period mean that other generators are required to fill the gap.

3. The utilization of back-up capacity declines

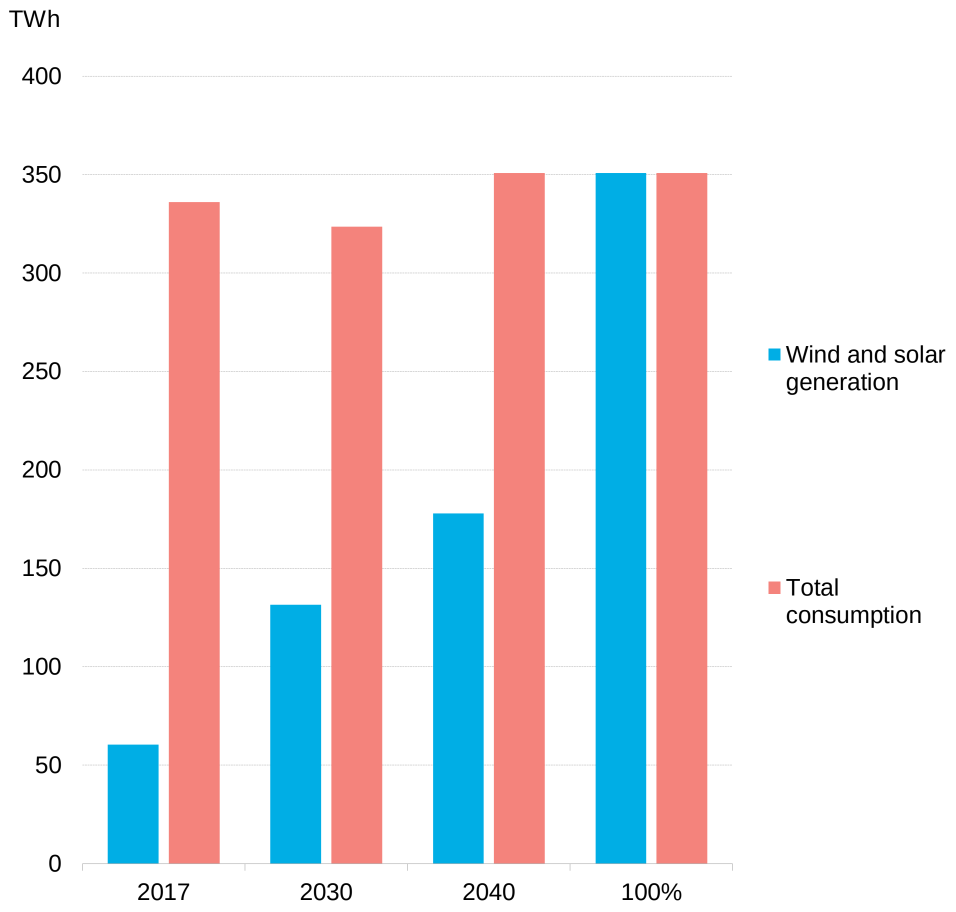
- Energy from wind and solar meets an ever-greater share of demand, reducing the energy required from other sources.
- This results in decreasing utilization of back-up capacity rather than plant closures, since these assets are still required to meet demand during periods of low wind and solar generation.

4. System volatility increases

- Historically, flexible generation sources were only required to adjust their output to match demand fluctuations. As wind and solar generation increases, these resources will need to adjust their output according to variations in both demand and supply.
- At very high penetration rates for wind and solar, such generating sources also need to cope with shutting down and starting up over short time intervals.

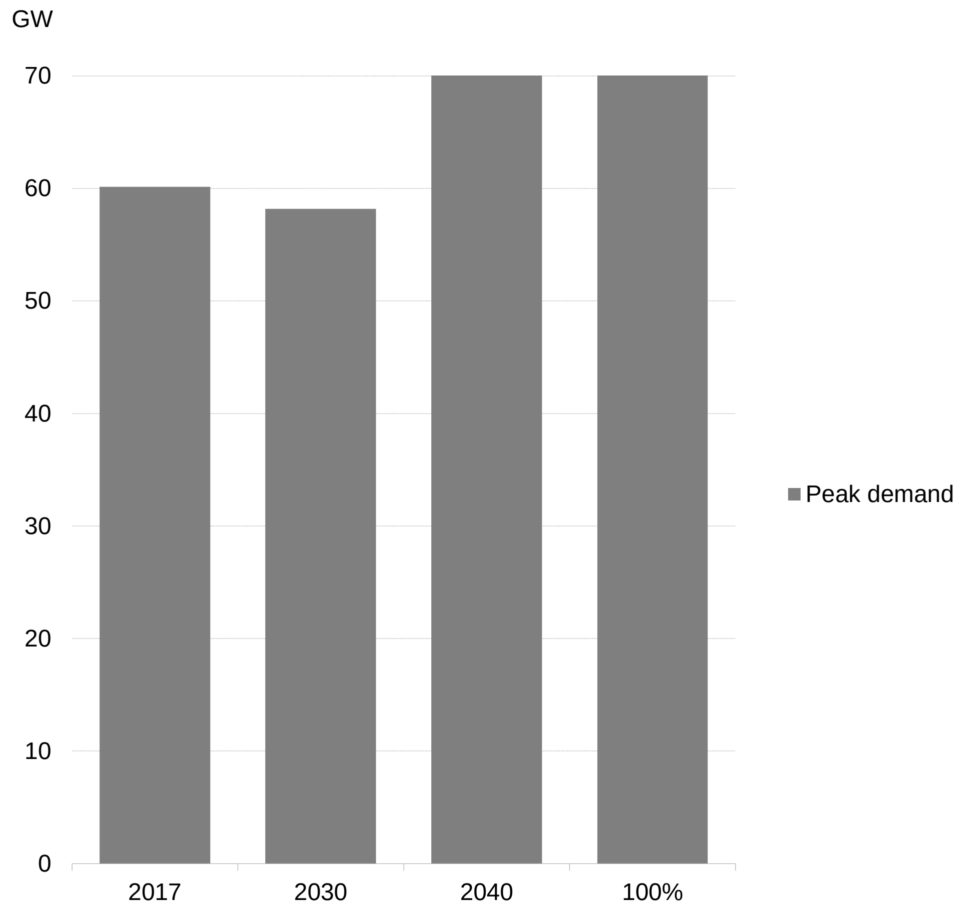
Four scenarios used in this analysis

Annual generation



Source: Bloomberg New Energy Finance

Peak demand



Source: Bloomberg New Energy Finance

Four scenarios used in this analysis

About the scenarios

- For our analysis of the U.K. flexibility gap, we looked at four scenarios* for wind and solar penetration, which we labelled:
  1. 2017
  2. 2030
  3. 2040
  4. 100%
- The first three scenarios (2017, 2030 and 2040) model a U.K. system with wind and solar penetration equivalent to these respective years in the BNEF New Energy Outlook forecast.
  - These scenarios explore what the flexibility gap would look like for the U.K., if the renewable deployments modeled in the New Energy Outlook were to come true.
  - The remainder of the generation stack (not wind or solar) is simplified to a single resource that we call 'other generation'
- In the fourth scenario, '100%', wind and solar generation over a year is equalt to annual electricity demand. However, because of timing differences, this does not mean, of course, that all demand can be met by wind and solar.
  - This is not an economically modeled scenario – unlike the 2017, 2030 and 2040 scenarios, which are outcomes of the New Energy Outlook. It is only included to illustrate an extreme case.

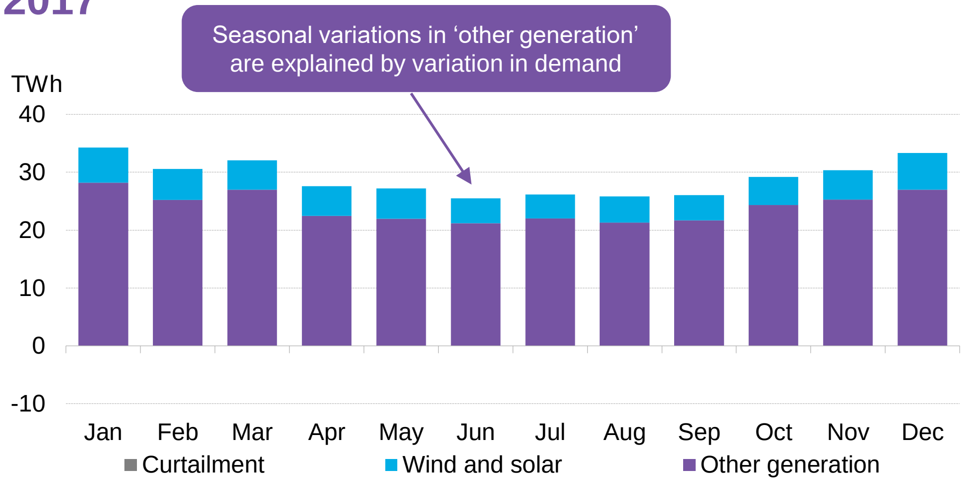
Note: we use 'scenarios' here to mean future penetration of wind/solar – not alternative trajectories for the energy system. They are different points on the same trajectory.

Key figures used in each scenario

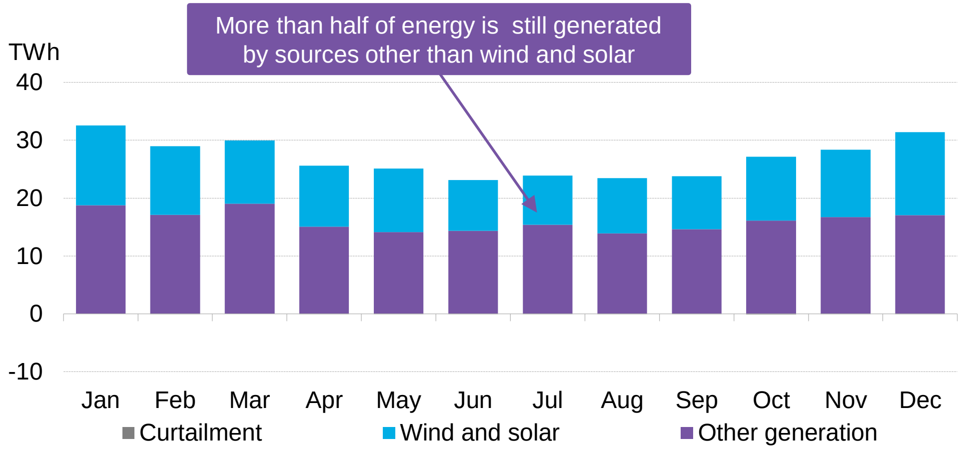
Scenario	2017	2030	2040	100%
Total demand (TWh)	336	324	352	352
Peak demand (GW)	60	58	71	71
Share of demand met by wind and solar (%)	18%	40%	50%	80%
Curtailment (TWh)	0	0.3	5	72
Onshore wind capacity (GW)	12	12	27	12
Offshore wind capacity (GW)	7	22	16	61
Solar PV capacity (GW)	13	18	33	69

Monthly generation

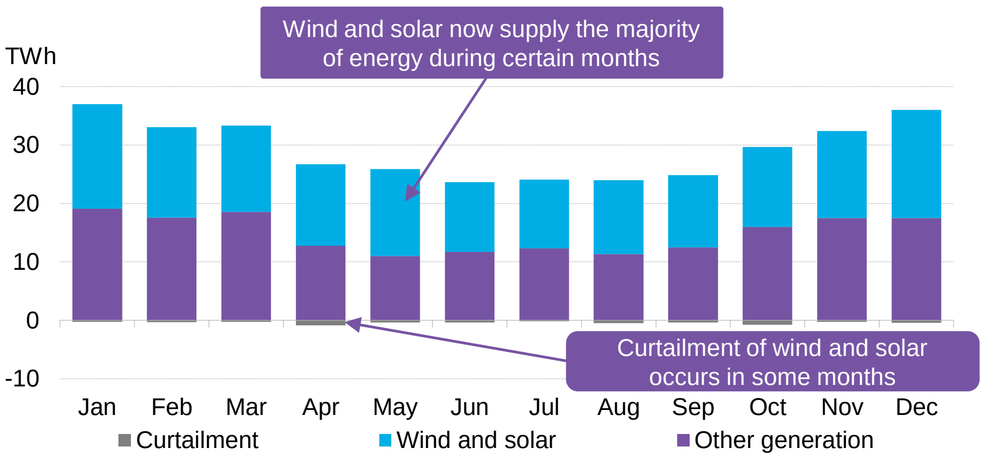
2017



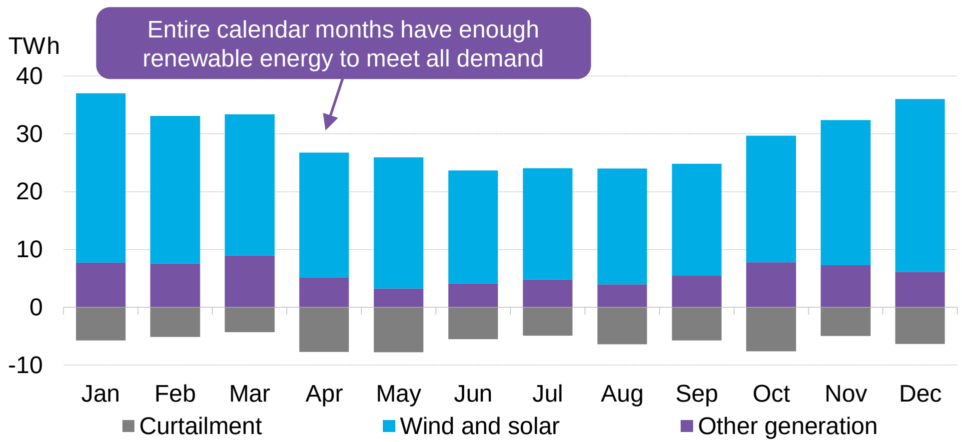
2030



2040



100%



Note: other generation includes all form of generation besides wind and solar, and can also be interpreted as 'net demand' – total demand net of wind and solar generation.

Monthly generation

Key trends

The charts above show how much of demand is supplied by wind/solar or other resources, at ***monthly*** granularity, for each scenario.

Two dynamics are apparent in the charts:

- **Decreasing 'other' generation:** the not-wind-or-solar element accounts for 82% of electricity demand in 2017, but this falls to 60% in 2030, and 50% by 2040.
  - However, even in the extreme scenario, where wind and solar generate enough for 100% of demand, 'other' sources are still needed to provide 20% of energy because of the mismatch between wind and solar generation and demand.
- **Increasing curtailment (wasting) of wind and solar energy:** In the absence of energy storage or demand shifting, the wasting of variable renewable energy – because of generation exceeding demand – grows from none in 2017, to 0.3TWh in 2030, and 5TWh in 2040.
  - However, excess renewable output never grows so large that it needs to be shifted from one month to the next. This only happens in the 100% scenario.

Scenario notes

2017

- At low penetration rates, wind and solar seasonality has a limited effect on the system. Instead, demand seasonality – high in winter, low in summer – explains most of the variability in the output of other generators.

2030

- Despite the growth in the share of variable renewables, other generators are still needed to meet more than half of demand.
- The first occurrences of wind and solar curtailment show that even at medium penetration levels, over-generation is an issue.

2040

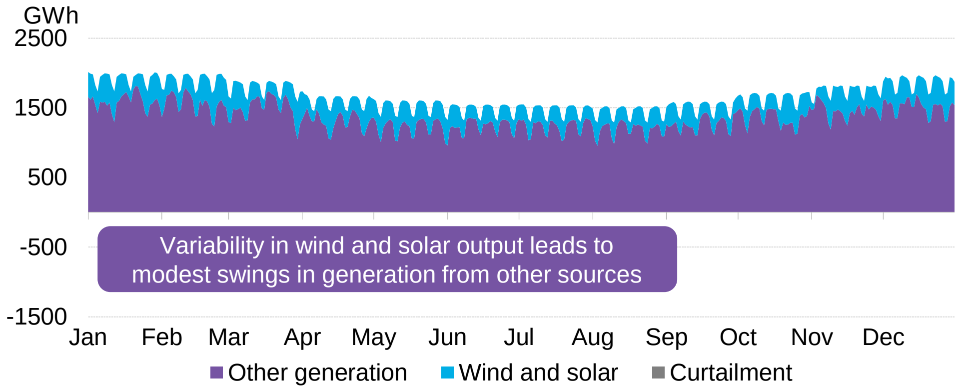
- Wind and solar output grows to supply half of annual electricity demand, and become the largest generation source during certain months. Other generators focus on providing back-up capacity.
- Curtailment starts to become a noticeable phenomenon, especially in months of low demand or high variable renewable output.

100%

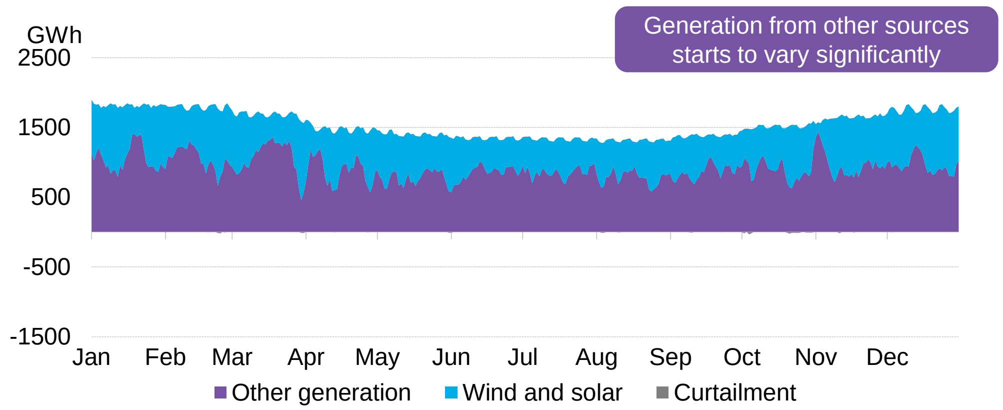
- Because wind and solar output does not always match demand, back-up generation is still needed – despite those sources providing enough electricity to meet all of demand.
- In some months, variable renewables generate more energy than required. This is where being able to shift output from one month to another becomes useful.

Daily generation

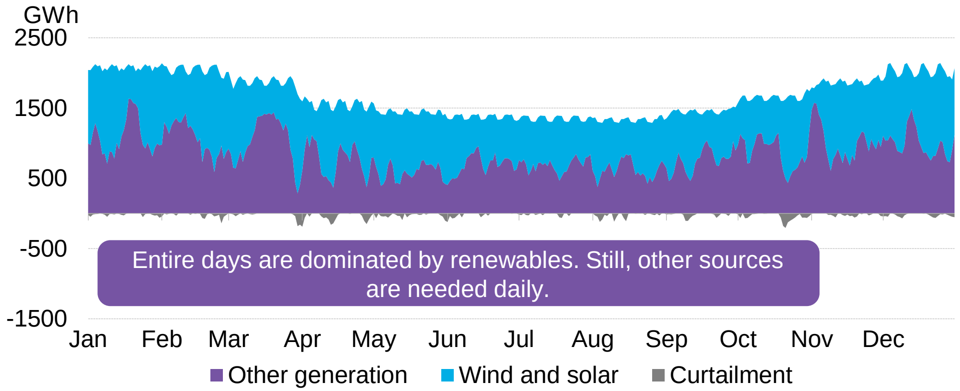
2017



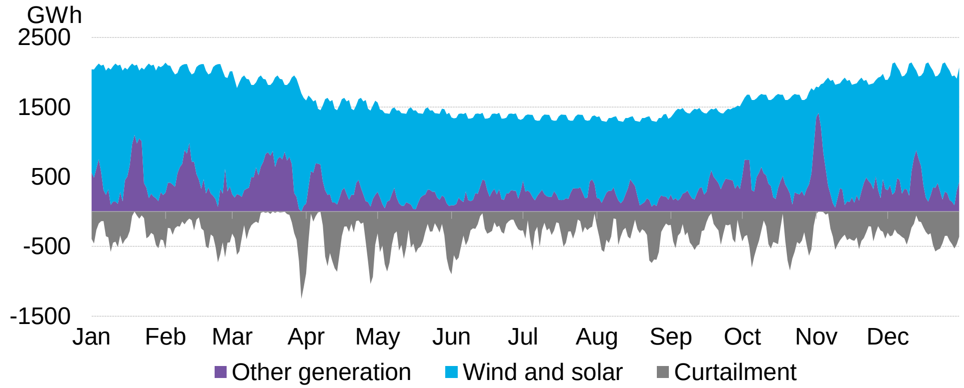
2030



2040



100%



Daily generation

Key trends

The charts above show how much of demand is supplied by wind/solar or other resources, at ***daily*** granularity, for each scenario.

Looking at the daily curve reveals a more detailed picture. The two main dynamics are:

- **Growing variability:** the magnitude of fluctuations in solar and wind output grows considerably from 2017 to 2030. As a result, ‘other’ generation output also experiences increasing levels of volatility.
- **There are still low (near-zero) wind and solar days**, even at high shares of renewables in 2040, requiring other sources to step in.
  - This is markedly different from the monthly charts shown previously, where every month has significant wind and solar generation. At the daily level, there is much more variation.

Scenario notes

2017

- Day-to-day swings in variable renewable output can be as high as 67%. A windy/sunny day, followed by a wind-still/cloudy one explains the most extreme swings.
- The penetration of wind and solar is still low. As a result, variable renewables never get close to exceeding daily demand.

2030

- More wind and solar means a more volatile system. The effects of insolation or wind speed changes are amplified by the capacity installed.
- As a result, in the course of 24 hours, total back-up generation might be required to vary its output by up to 41%.

2040

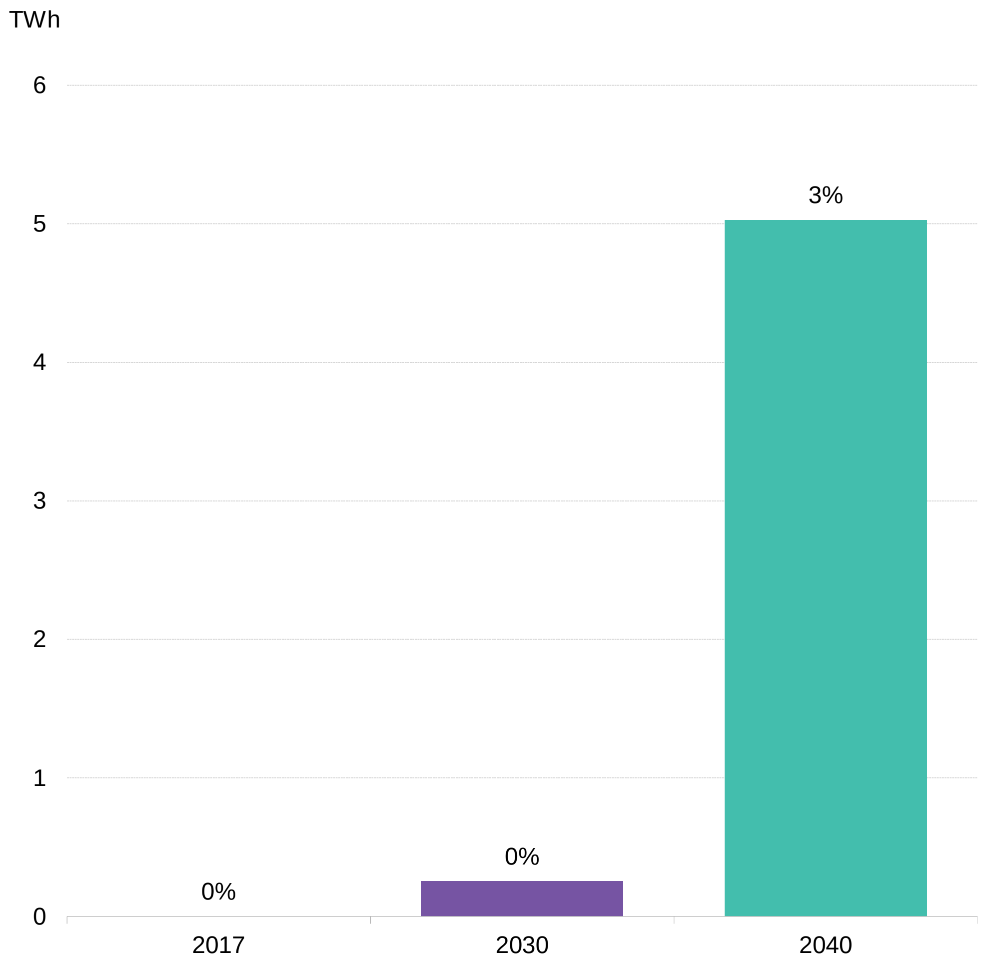
- Other generators see large swings in their output, and utilization. There are occasions when variable renewable output is so high that back-up plants only provide 17% of the daily electricity. In low wind and solar days, their share grows to 88% of daily electricity.

100%

- With wind and solar able to provide as much energy as needed, other generators become a pure back-up option. Yet, even in this scenario, there are days when other sources are required to supply more than 79% of daily power generation.

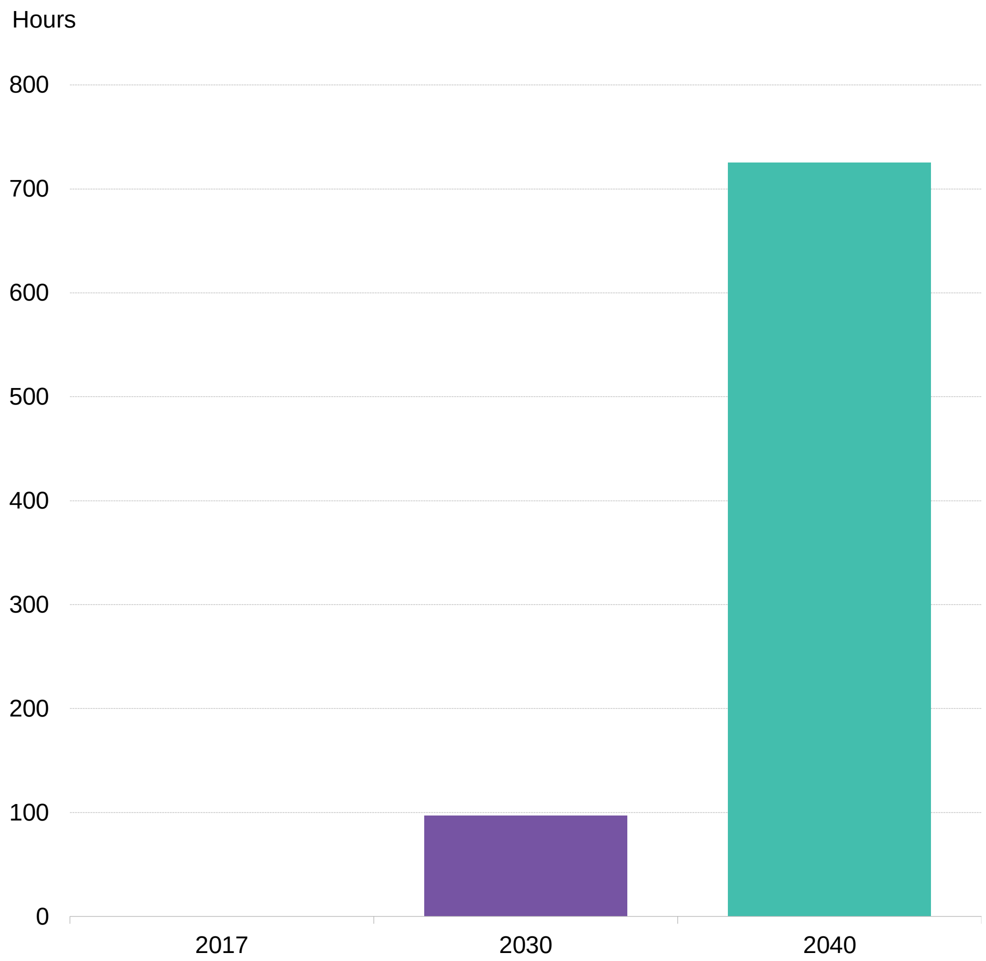
Curtailment of wind and solar generation

Wind and solar energy curtailed by scenario



Source: Bloomberg New Energy Finance

Hours of wind and solar curtailment by scenario



Source: Bloomberg New Energy Finance

Curtailment of wind and solar generation

Key trends

- **Curtailment of wind and solar becomes increasingly common** as penetration rises. This happens when more wind and solar power is generated than is required at that point in time.

- **Even in 2040, only a small minority of energy generated from solar or wind is curtailed.** However, these curtailment figures represent a lower bound, as other system constraints can lead to the wasting of such energy. These constraints include:
  - Shortfall of transmission capacity to transport solar / wind energy to demand centers.
  - Inflexibility of other parts of the energy system, making renewable electricity curtailment the cheapest option for balancing.

- **Curtailment represents an opportunity for technologies that can store or shift energy**
  - These include batteries and other energy storage technologies (shifting supply), or demand-side response and dynamically-charging electric vehicles (shifting demand).
  - Interconnectors can also play a significant role, to enable export of renewable energy at times of surplus.

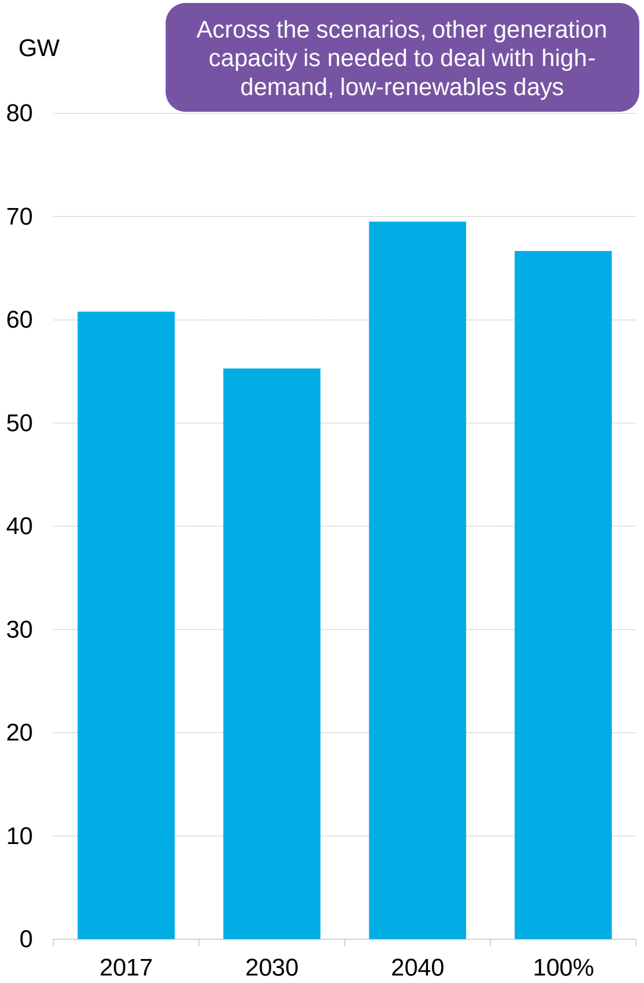
Scenario notes

- **In 2030, less than 1% of wind and solar output is wasted**
  - Curtailment occurs around 1% of the time.

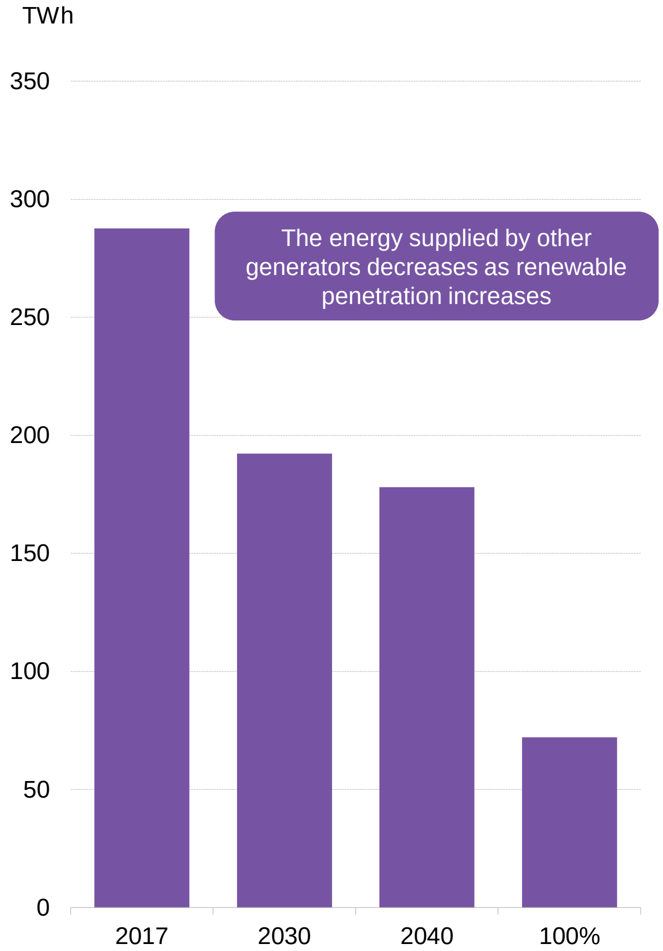
- **By 2040, curtailment jumps to 3%** of total energy supplied by renewables
  - There are over 700 hours when renewable output exceeds demand – equivalent to about 1 month.

Back-up capacity & declining utilization

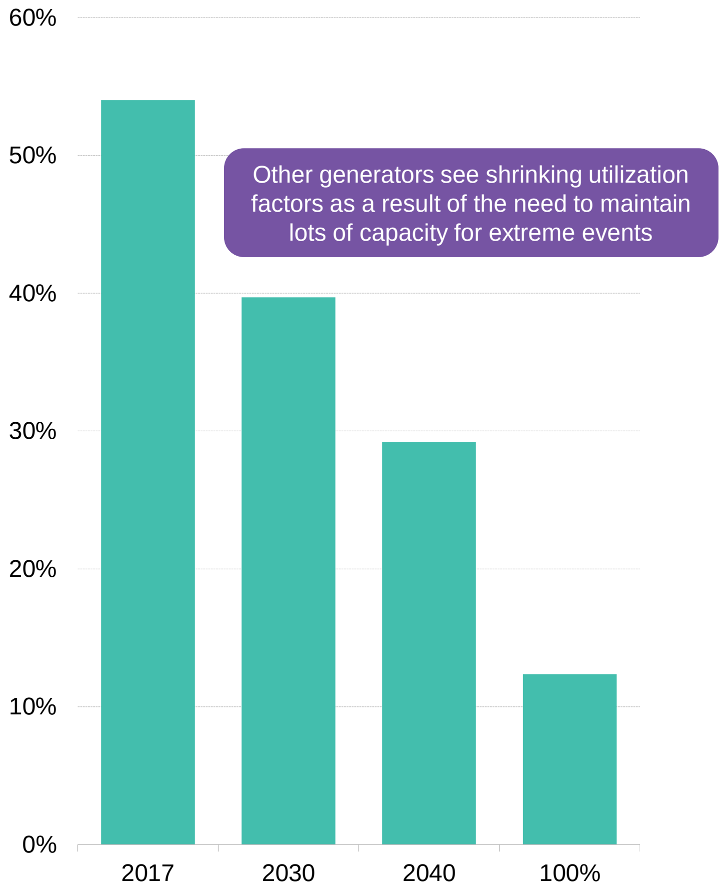
Peak output of 'other generators'



Energy generated by 'other generators'



Utilization of 'other generators'



Back-up capacity & declining utilization

Key trends

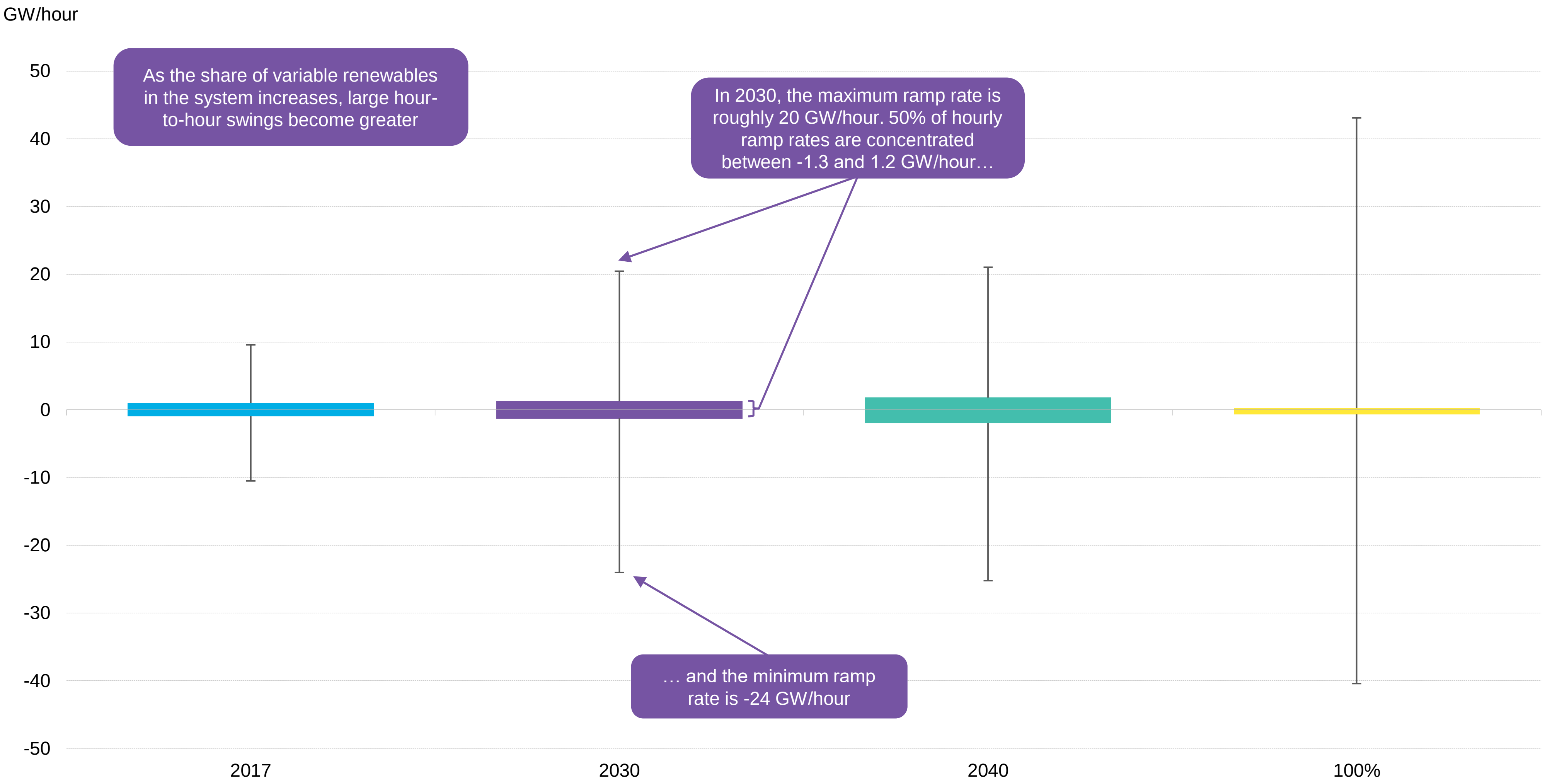
- **In all scenarios, there are some hours when most of demand has to be met by other (non-wind/solar) sources.** As a result, between 55GW and 70GW of back-up are still needed, despite the presence of much higher wind and solar capacity. These can be provided by dispatchable generation, or other sources such as interconnectors, energy storage and demand response.
- **But as wind and solar grow, they meet higher shares of demand**, crowding out other generating sources. Output from non-wind and non-solar generators is expected to shrink by 33% between 2017 and 2030, and by 38% to 2040.
- **This drives down the utilization rate of 'other' sources used for back-up.** Today, non-wind/solar generators run at around 54% utilization, but that is expected to fall to 40% in 2030, and 29% in 2040.
- These trends point to several possible implications:
  - A growing opportunity for short-run flexibility options, such as energy storage and flexible demand.
  - An increasingly difficult operating environment for conventional plants, as they struggle to earn a return from fewer operating hours.
  - This could lead to more instances of scarcity, accompanied by very high power prices – or growing out-of-market payments to keep conventional generators online as power market revenues fall.

Scenario values

Scenarios	2017	2030	2040	100%
Peak output of other generators (GW)	61	55	70	67
Energy supplied by other generators (TWh)	288	192	178	72
Utilization of other generators (%)	54	40	29	12

Growing system volatility

Distribution of hourly ramp rates across the year



Growing system volatility

Key trends

The chart above shows how often ‘other resources’ (non-wind/solar) in the system have to ramp up and down, to accommodate hourly fluctuations in demand and wind/solar output. This is shown as a box plot illustrating the distribution of all the hourly ramp rates in a year.

- As wind and solar are added to the system, other sources have to ramp up and down more quickly, and more often.
- **Extreme system volatility events increase** as the share of variable renewables rises. This is calculated as the highest hourly upward (**ramp-up**) or downward (**ramp-down**) change in output required from other generators to make up for the shifts in wind and solar output and in demand.
- **Extreme ramp rates stress the system,** as failure to meet them can result in oversupply (requiring energy wastage) or under-supply (threatening system stability). Ramping is also an issue because conventional generators are generally most efficient when run at stable output. During changes in output, efficiency drops and costs increase.
- **Increased ramping requirements could be an opportunity for newer technologies** such as battery storage and certain types of flexible demand, which can alter their states of generation/consumption quickly without major cost implications.
- The chart above only addresses hourly changes in demand and wind/solar output. It does not account for intra-hour fluctuations, for example to manage forecasting errors, or to maintain system frequency.

Scenario notes

2017

- The highest ramp-up is around 10GW in an hour, and the highest ramp-down is around 11GW
- This corresponds to one third of the current U.K. gas fleet turning on or off in one hour

2030

- The highest ramp-up is around 20GW/hour and the highest ramp-down is 24GW/hour
- This corresponds to around 40% of the current U.K.’s gas, coal, and nuclear plants turning on or off in one hour

2040

- The highest ramp-up climbs to 21GW in an hour, and the highest ramp-down is around 25GW/hour
- These changes correspond to around 20% of the U.K.’s entire current generation fleet turning on or off in one hour

U.K.: hourly and daily variability

Analyzing hourly and daily issues

Managing hourly and daily variability

This section explores the short-term dynamics of a high-renewables system in the U.K., focusing on issues that arise at the ***hourly*** and ***daily*** horizon. To do so, we have applied five years of historical solar/wind production data to each scenario.

Challenges and opportunities

All four of the issues identified in the previous section are apparent at the daily/hourly level, creating opportunities for technologies that can address them:

- **Reducing volatility:** hour-to-hour variability in demand and wind and solar output creates an opportunity for flexible generation or energy storage / shifting technologies that can smooth this out.
- **Reducing the curtailment of renewables:** excess renewable generation in some hours can be better utilized by shifting it to other hours, or making sure there is enough demand to absorb it.
- **Reducing the need for back-up generation capacity:** technologies with better-suited economics can be deployed and operated during extreme events, reducing the need for more expensive back-up options.
- **Increasing generation asset utilization:** by reducing the back-up capacity requirements, less generating capacity is required, increasing the utilization of the remaining capacity.

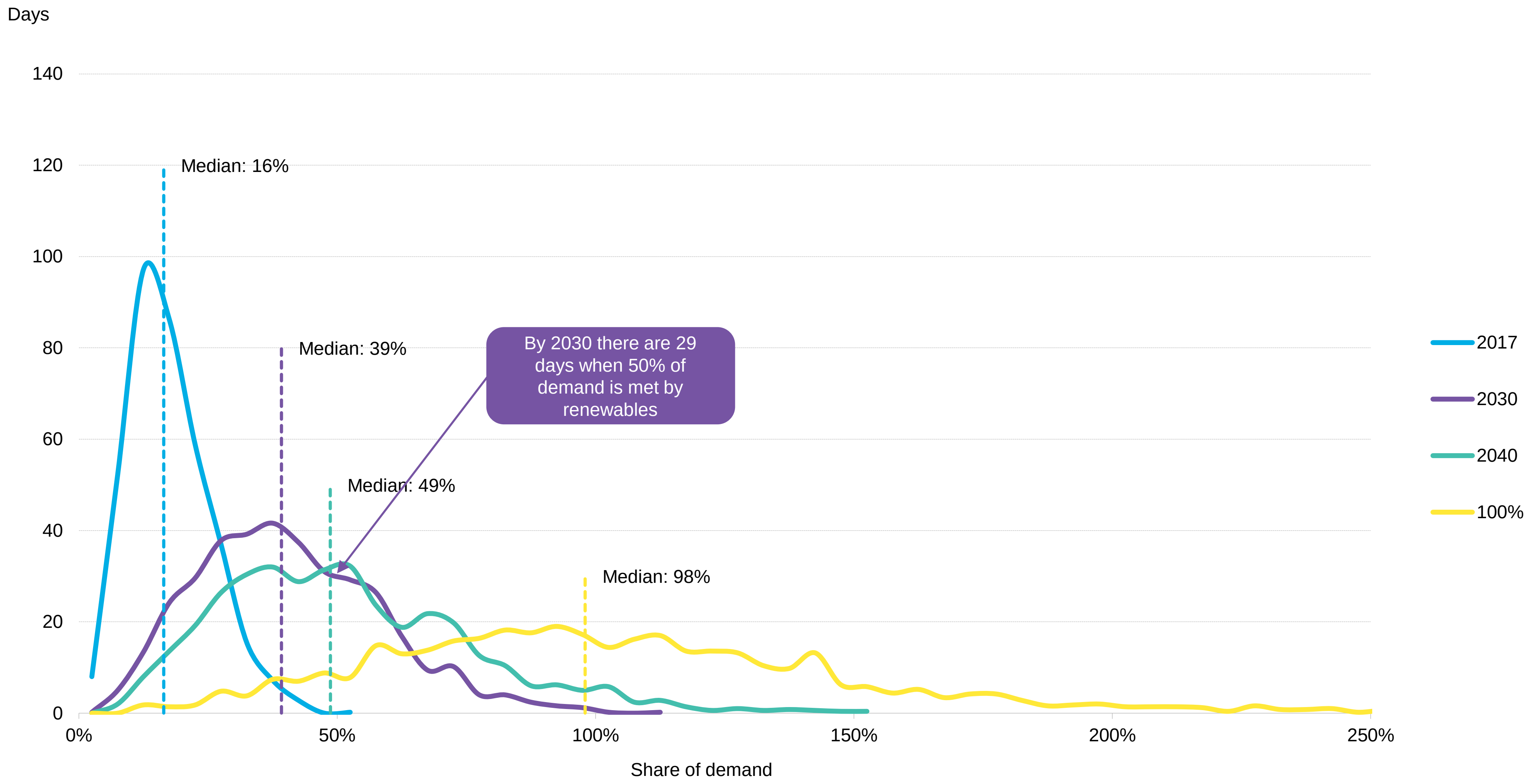
Technology options

To address these issues, system operators can call on a variety of technologies with various advantages and disadvantages, including:

- **Peaking gas plants:** a relatively low capital expenditure approach, with high running costs. Peaking plants can help during peak events, and are very agile, but they cannot address curtailment.
- **Demand response:** reduction of power demand through DR technologies is a relatively low-capex approach, but often with a high per-use opportunity cost. Demand response can help reduce peak requirements by reducing load in hours of high system stress.
- **Flexible electric vehicle charging:** by taking control of EV charging, demand can be increased when curtailment happens and reduced during a peak event. This is a low-capex, low-opex approach, but requires mass adoption of EVs and smart charging.
- **Batteries:** this is a high-capex, low-opex approach, though their cycle life also imposes an opportunity cost of sorts. Batteries are well-placed to address all of the issues above in the short term (hourly/daily). By modifying their charge/discharge rate they can reduce system volatility. They can also reduce curtailment by charging up during high wind and solar output hours. And they can reduce the need for peak generation by discharging at maximum output during hours of low renewable electricity output.
- **Interconnection:** greater interconnection with neighboring countries will allow power to be exported at times of excess, and imported when required to meet gaps in renewables production – assuming that neighboring countries are not suffering the same issues at the same time.

Variable renewable generation distribution

Number of days for which renewable generation makes up X% of demand



Variable renewable generation distribution

Key trends

The chart above shows how often wind and solar account for a certain proportion of daily demand. For example, the blue curve shows that in 2017, wind and solar could account for 25% of demand on roughly 60 days of the year, but they never account for more than 50% of demand in a day.

- As the share of wind and solar in the system increases, there are more days when they meet more of demand. This can be seen in the way the curves shift to the right for later years.
  - This also means that there are fewer days when wind and solar are insignificant. For example, by 2030 there are already rather few days when wind and solar produce less than 25% of demand. It will be much more common for wind and solar to produce around 25-60% of demand.
- The curves also become much flatter in later years (especially in the extreme 100% case). This indicates a much greater range of possibilities for how much wind and solar there is relative to demand on a given day:
  - In the 2040 scenario, on a given day wind and solar could produce as much as 150% of demand, or as little as 5%. To put it another way, wind and solar are about as likely to provide 100% of demand as they are to provide 10% of demand.
  - From a system operation perspective, this implies a much broader range of daily scenarios to prepare for.
- The next few pages explore these trends by showing hourly data for typical and extreme (high- and low-renewable) days.

Scenario notes

2017

- On a typical (median) day, wind and solar generate enough to meet 16% of demand.
- Wind and solar occasionally meet more than about 30% of demand on a given day. In very rare occasions they reach 50%.

2030

- On a typical (median) day, wind and solar generate enough to meet 39% of demand. Even on the lowest day, they meet 5% of demand.
- Wind and solar contribute more than half of demand for 106 days, or 30% of the year. They typically contribute between 27% and 52% (this is the inter-quartile range).
- There are also the first extreme days, when wind and solar generate more than needed – but these occurrences are still rare.

2040

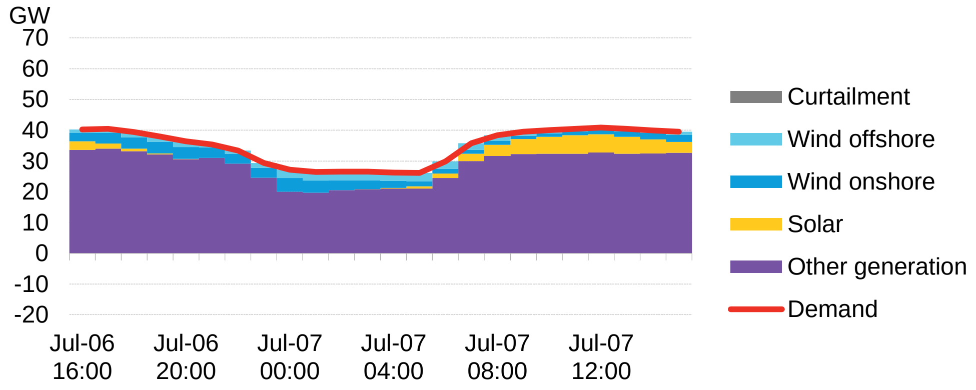
- On a typical (median) day, wind and solar generate enough to meet 49% of demand. Even on the lowest day, they meet 5% of demand.
- Wind and solar contribute more than 49% of demand for over half of the year. There are around 17 days when wind and solar over-generate. This over-generation can reach occasional extremes, surpassing 125% of demand.

100%

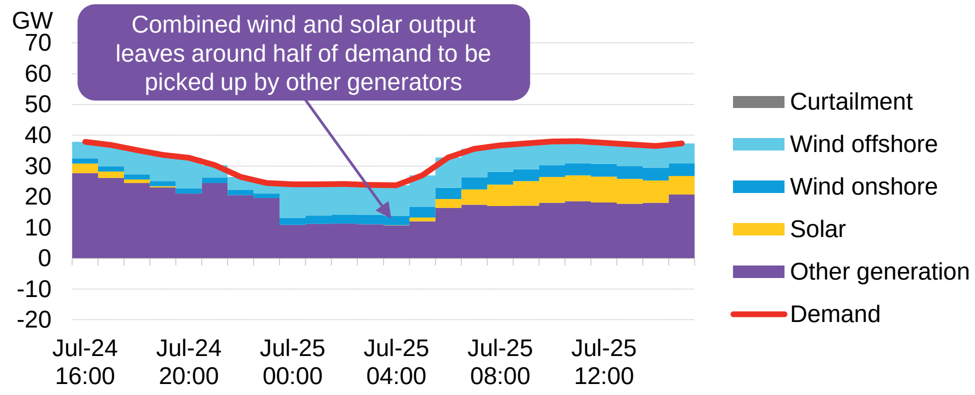
- In the most extreme case, wind and solar can generate more than double daily demand.

Median wind and solar 24-hour period

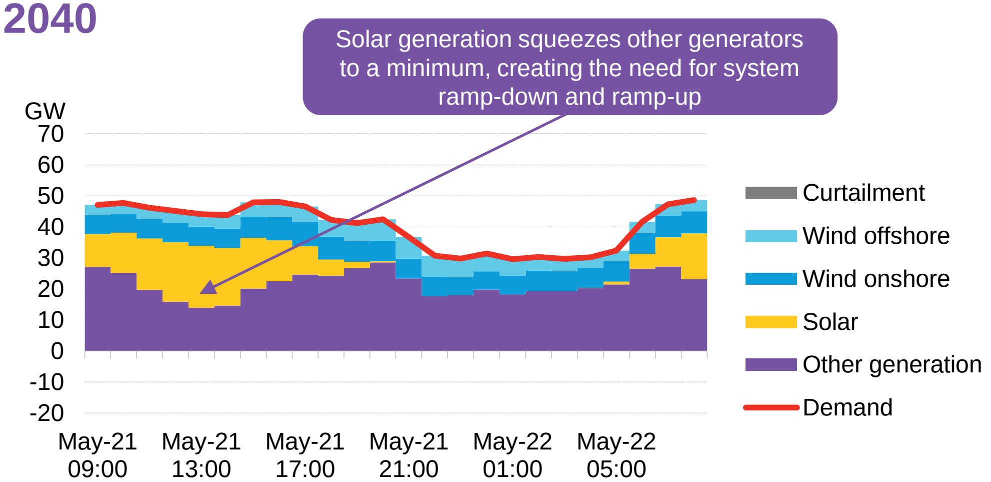
2017



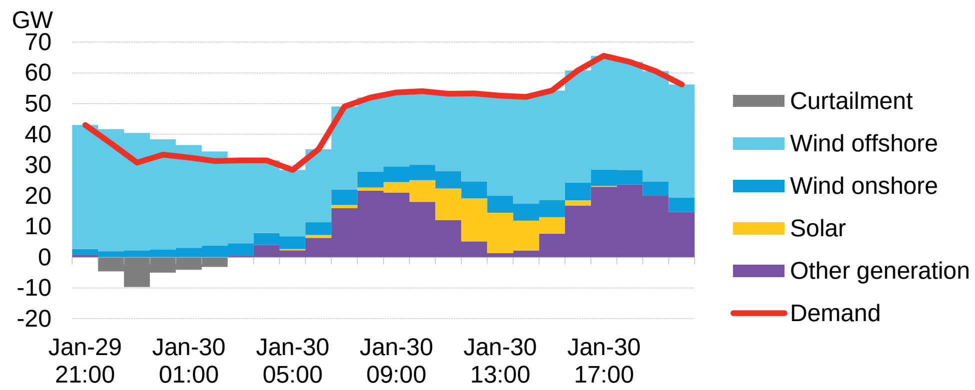
2030



2040



100%



Note: definition of the median renewable 24 hour period: 50% of 24-hour periods in the year have a higher share of renewable generation and 50% of 24-hour periods in the year have a lower share of renewable generation. These are 24-hour periods, not calendar days – so there are 8,736 24-hour periods in a year.

Median wind and solar 24-hour period

Key trends

The charts above show hourly production and demand for the *median day (by wind and solar share)* in each scenario. The purple 'other generation' columns show what other energy sources must provide in order to match hourly demand, after wind and solar production are accounted for.

- Other generation provides less and less energy in future years. This is to be expected for the typical day, as more wind and solar are added.
- Increasing wind and solar output introduces more hourly volatility, so other generation must also flex more to accommodate this. This can be seen in the larger up- and down-ramps of the purple columns in later scenarios.
- The maximum other generation needed ranges from 34GW in the 2017 scenario, to 29GW in the 2030 and 2040 scenarios, and 24GW in the 100% case.
- There is no curtailment of wind and solar on a median day (except for the 100% case, when wind picks up in the middle of the night).

Scenario notes

2017

- None of the described issues are evident on a median day. Other generation adjusts gradually to account for demand changes and modest shifts in wind and solar production.

2030

- Volatility in variable renewable output starts to drive other generators to ramp more dramatically. We also start seeing how other generators' output is kept subdued by offshore wind running flat out during the course of a day.

2040

- Volatility in renewables output becomes more significant. A large slug of solar means that other generators are forced to ramp down in the middle of the day. As the sun sets and solar generation decreases, other generators need to ramp up in a matter of hours.

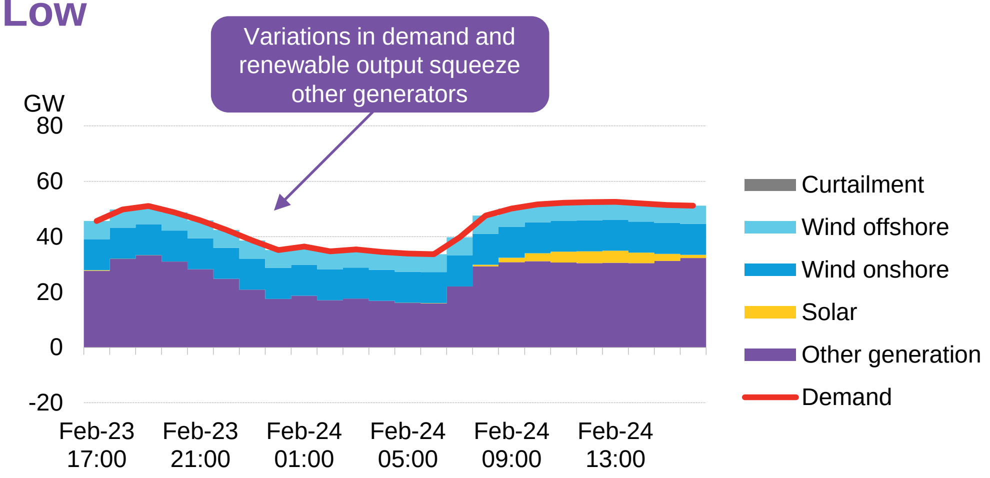
100%

- The median day in the extreme case falls on a winter day in January. The day is dominated by wind generation, a part of which is curtailed overnight. Other generation is called upon to pick up the slack of the morning demand increase, when solar has not started generating yet. But solar power in the middle of the day means these plants need to shut down after just a few hours.

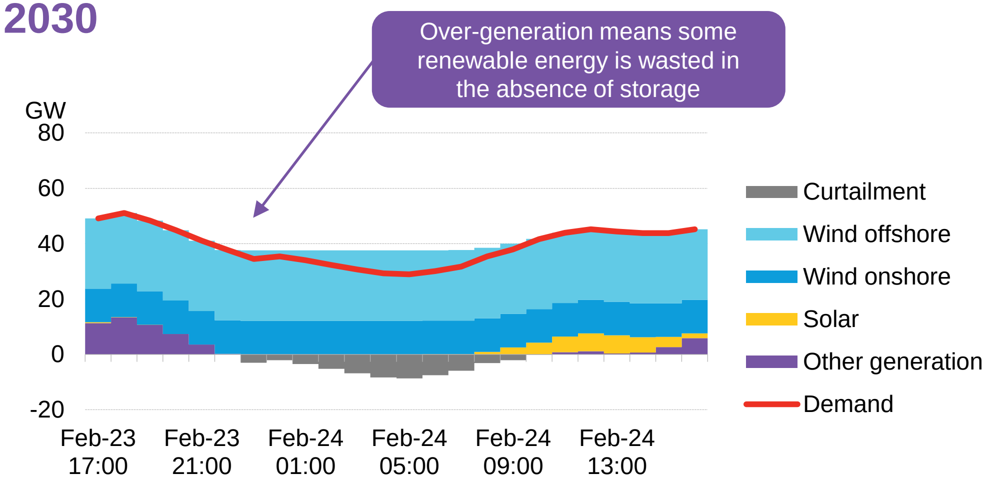
Note: definition of the median renewable 24 hour period: 50% of 24-hour periods in the year have a higher share of renewable generation and 50% of 24-hour periods in the year have a lower share of renewable generation. These are 24-hour periods, not calendar days – so there are 8,736 24-hour periods in a year.

Highest wind and solar 24-hour period

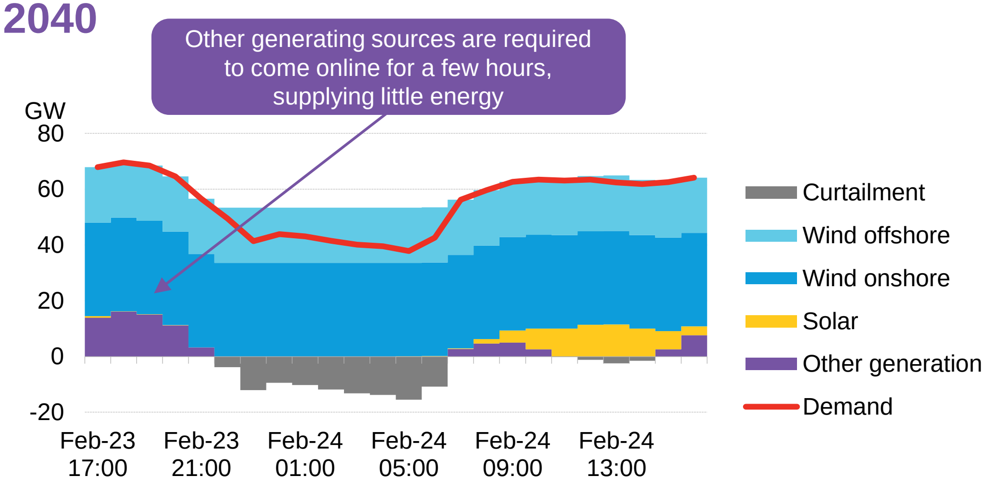
Low



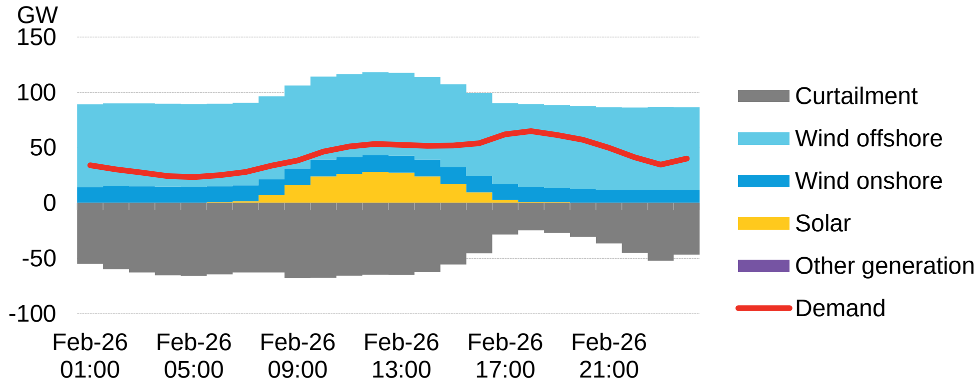
2030



2040



100%



Note: 24-hour periods where wind and solar account for the highest share of demand in the year. These are 24-hour periods, not calendar days – so there are 8,736 24-hour periods in a year.

Highest wind and solar 24-hour period

Key trends

The charts above show hourly production and demand, for the *highest day (by wind and solar share)* in each scenario. The purple 'other generation' columns show what other energy sources must provide in order to match hourly demand, after wind and solar production are accounted for. Grey shows curtailment, when wind and solar alone exceed demand.

Looking at the highest wind/solar production day allows us to see the most extreme daily dynamics at work. We can see that:

- On these highest wind/solar days, the role of other energy sources is massively diminished. This happens as soon as 2030, and raises important questions about how conventional and nuclear generators will be able to operate in a high-renewables system. Their ability to flex – or disconnect completely – will become increasingly relevant.
- This also raises questions about how system frequency will be managed, if the power system is dominated by asynchronous generators at certain times.
- Curtailment becomes an issue on these highest-wind/solar days – and could be greater if other generators are not able to switch off, or if grid constraints become a bottleneck. However, we note that overall annual curtailment remains below 1% of wind/solar production in 2030, and 3% in 2040 – the days shown here are the extreme case.

Scenario notes

2017

- The highest wind and solar 24-hour periods start to squeeze other generators, but they still play an important role.

2030

- There are days when wind and solar generate nearly enough to meet all of demand – though a small amount of other resource is still required for a few hours.
- On these extreme days, there are hours of excess energy that will need to be curtailed or absorbed.

2040

- Days when wind and solar energy is enough to meet almost all of demand are more common – but again, some other resource is still needed at times.
- The volatility of wind and solar means that other generators need to be on stand-by to step in when there is a sudden shortfall in supply. This kind of short-term peak could be managed in part using energy storage or flexible demand.

100%

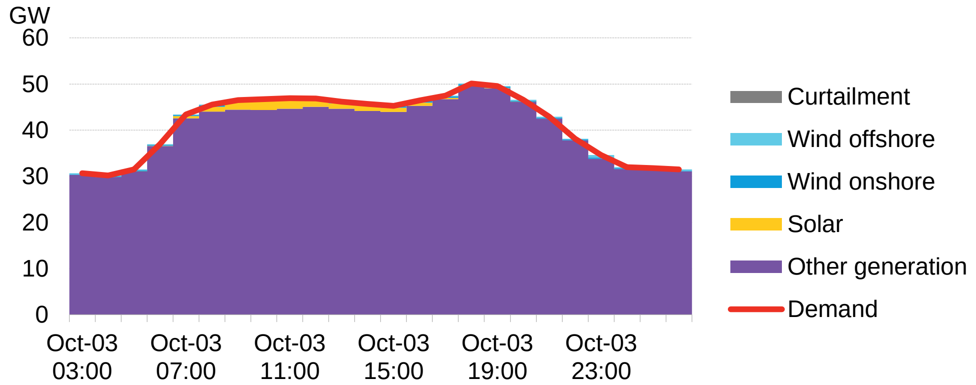
- This is the most extreme day of the most extreme case. Wind and solar produce far more energy than the system needs.

Note: 24-hour periods where wind and solar account for the highest share of demand in the year. These are 24-hour periods, not calendar days – so there are 8,736 24-hour periods in a year.

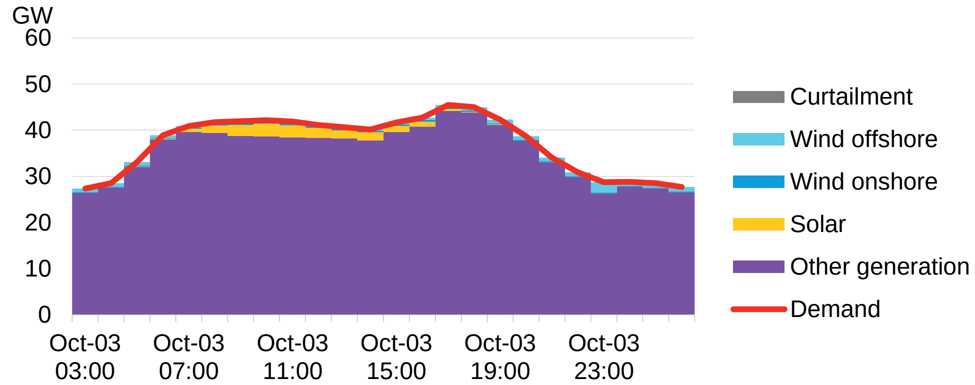
U.K.: hourly and daily variability

Lowest wind and solar 24-hour period

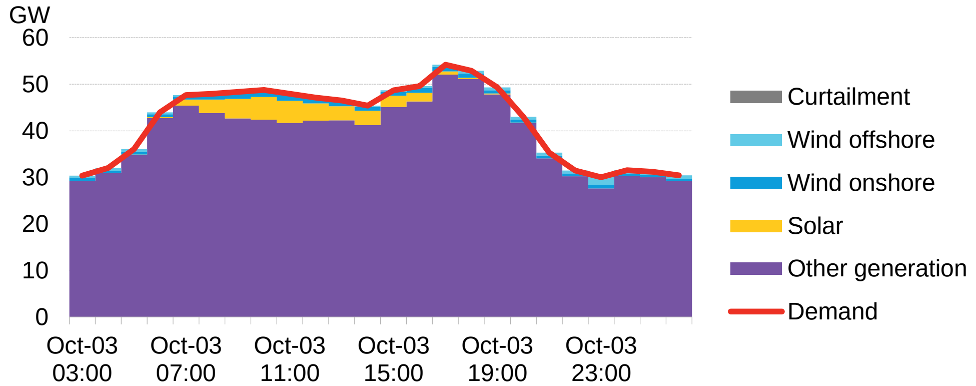
2017



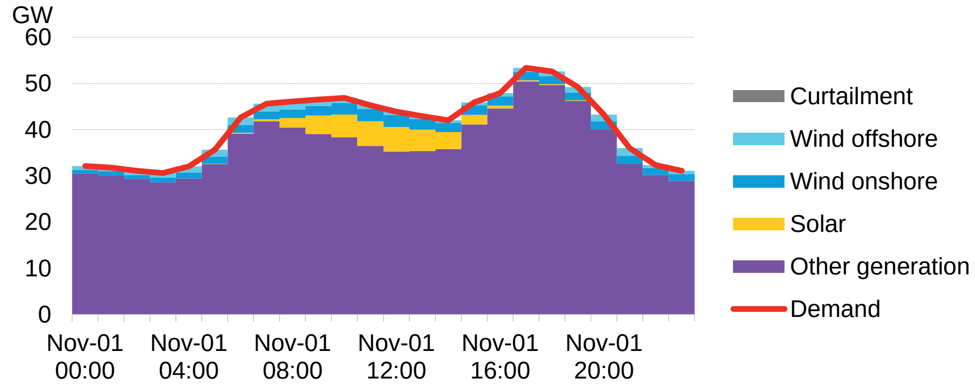
2030



2040



100%



Note: 24-hour periods where wind and solar account for the lowest share of demand in the year. These are 24-hour periods, not calendar days – so there are 8,736 24-hour periods in a year.

Lowest wind and solar 24-hour period

Key trends

The charts above show hourly production and demand for the *lowest day (by wind and solar share)* in each scenario. The purple 'other generation' columns show what other energy sources must provide in order to match hourly demand, after wind and solar production are accounted for.

- Even with the addition of large amounts of wind and solar capacity, there will be days when output from those sources will be close to zero. In the U.K. in 2040, this extreme occurs on a winter's day when there is cloud cover but little wind.
- Over such days, other generating sources will have to contribute energy and power.

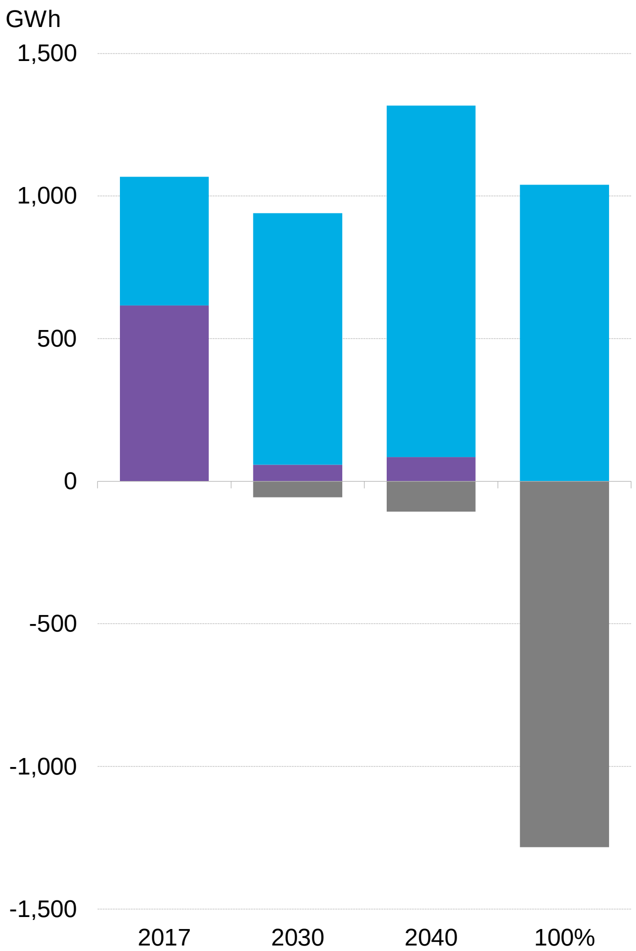
Scenario notes

- In the 2030, 2040 and 100% scenarios, there is still some wind and solar production, even on the most extreme low day. However, the overall picture remains the same as in 2017 – the vast majority of demand must be met by other sources.

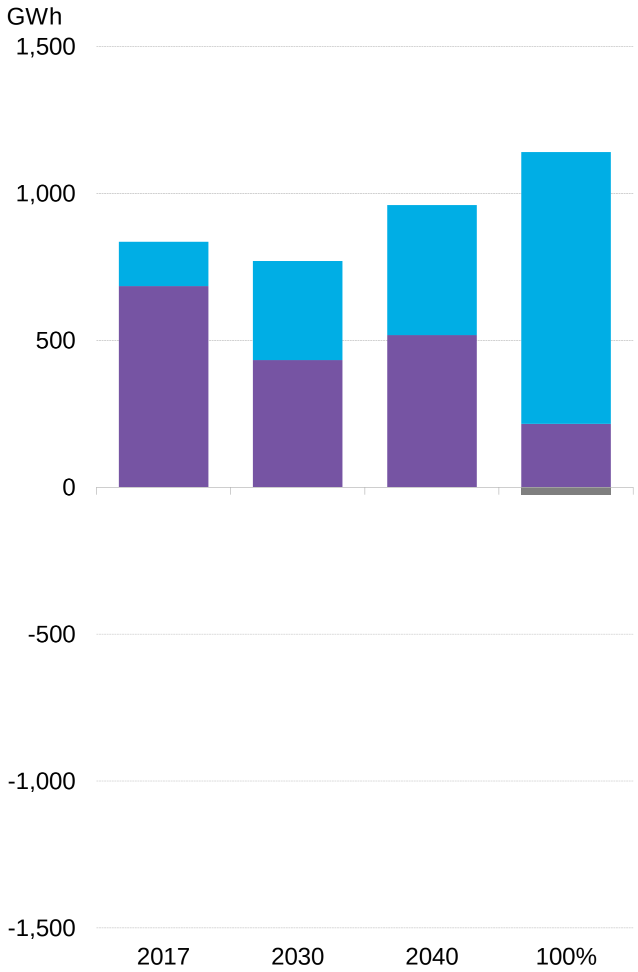
Note: 24-hour periods where wind and solar account for the lowest share of demand in the year. These are 24-hour periods, not calendar days – so there are 8,736 24-hour periods in a year.

Summary of challenges and opportunities

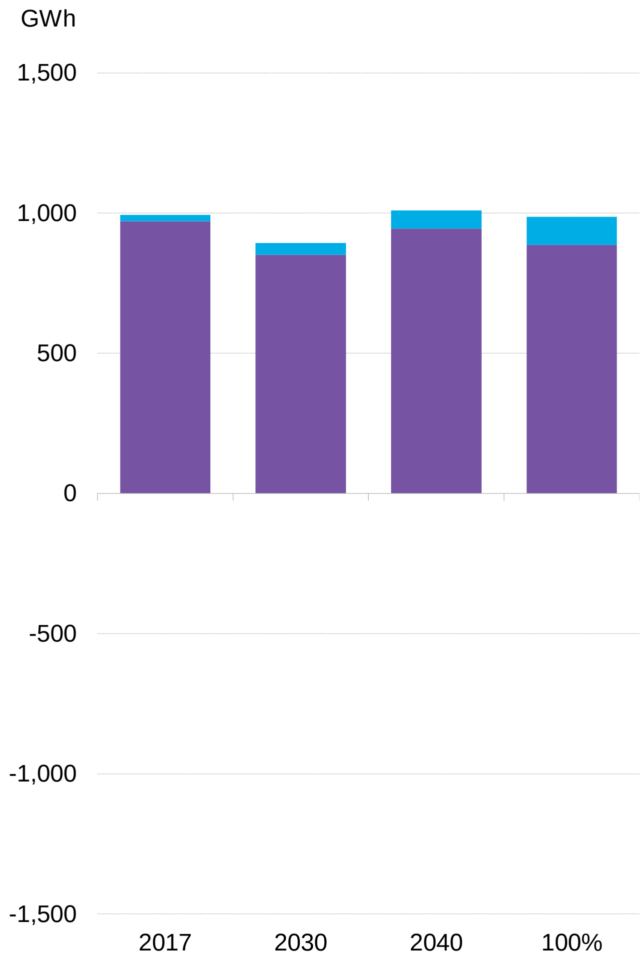
Highest renewable 24-hour period generation breakdown



Median renewable 24-hour period generation breakdown



Lowest renewable 24-hour period generation breakdown



■ Curtailment ■ Wind and solar ■ Other generation

Summary of challenges and opportunities

Challenges

- **Volatility**
  - The demands placed on other sources of energy can be very volatile hour-to-hour, especially on non-extreme days (where wind and solar generate some, but not the vast majority, of demand).
- **Curtailment**
  - The highest renewable energy output days lead to significant curtailment in all scenarios, with the exception of 2017.
- **Back-up is required in all scenarios**
  - Across all scenarios, the lowest variable renewable generation days require other sources to step in and meet almost 100% of electricity and capacity requirements.
  - Over median/typical days, other generating sources will be needed by the system to plug short-term gaps that variable wind and solar cannot meet.
  - Even on the highest wind and solar days, some hours in 2017-40 require small amounts of other generation.
- **Low generation asset utilization**
  - Power generators that provide back-up need to be sized such that they can meet peak demand, but they will operate at lower utilization rates as wind and solar grow. This is likely to drive up unit costs of generation for these plants.

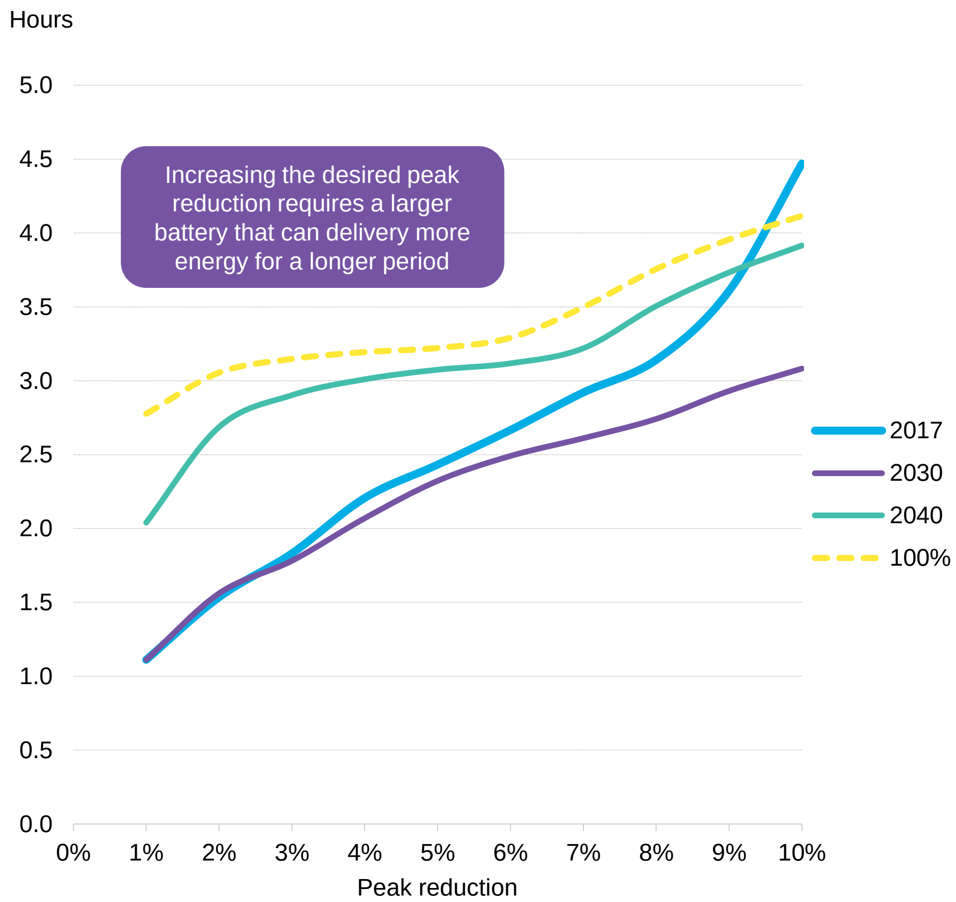
Opportunities for new technologies

- **Absorbing volatility**
  - Batteries and some sources of flexible demand can quickly adjust their charging/discharging patterns to smooth out volatility.
- **Reducing the curtailment of renewables**
  - As a form of flexible demand, electric vehicles can shift their charging within the day to coincide with high renewable generation periods, avoiding curtailment.
  - Batteries can be used to store some of the excess energy and deploy it at later hours, reducing the need for other generators to come online.
- **Reducing the need for back-up generation**
  - Demand response technologies can help reduce demand when the system is stressed. Electric vehicles can also avoid charging at these times.
  - Batteries can charge up as a peak event is approaching and discharge during the peak event.
- **Increasing generation asset utilization**
  - If these technologies are appropriately deployed and optimized, this can help to reduce system peak requirements. This in turn would mean that less back-up generation is required, increasing the utilization of the remaining capacity.

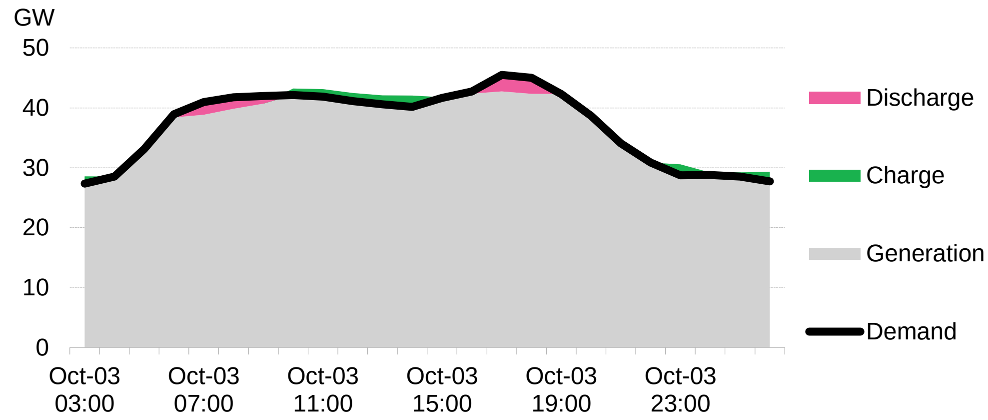
U.K.: hourly and daily variability

Case study: batteries to manage hourly peaks

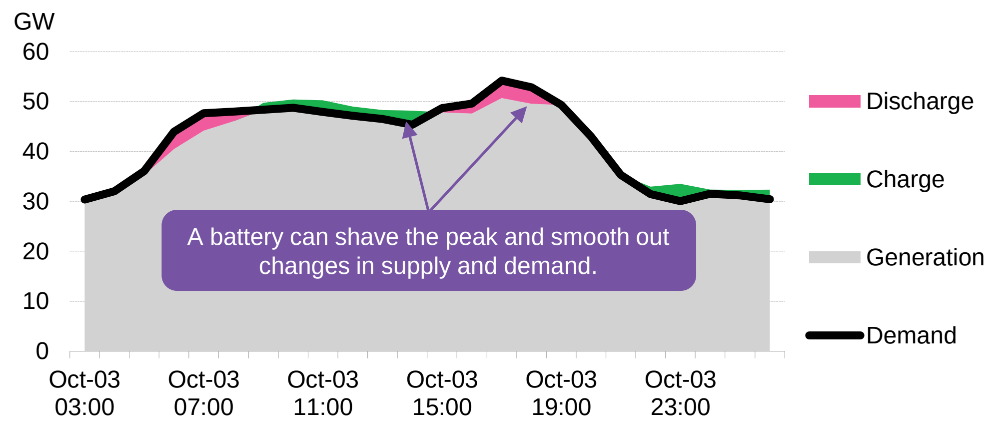
Peak shaving (size of battery required in hours of storage capacity for a desired peak reduction)



5% peak reduction with battery, 2030



5% peak reduction with battery, 2040



Case study: batteries to manage hourly peaks

Peak shaving case study

- **Batteries can help shave peaks**. They can charge when the system is not under stress, during hours of low to moderate output from other generators, and discharge when demand peaks. This reduces the maximum capacity of other generators needed in the system.
- **Longer peaks means bigger batteries.** To reduce peaks further does not just require more batteries, but also bigger batteries. Not only is more battery capacity required (MW) but, as remaining peak durations inevitably get longer, these batteries are also required to hold more energy (MWh).
  - For example, to reduce peak capacity in 2040 by 4% takes a 3-hour battery, whereas to reduce peak by 8% takes a roughly 3.5-hour battery.

Other use cases for batteries

- Batteries are suited to addressing other short-term issues that arise from increasing penetration of wind and solar.
  - **Low utilization of other generation:** by reducing the peak generation capacity requirements, the average utilization of the remaining generators will increase.
  - **Variability**: batteries can quickly swing from charging to discharging, offsetting changes in variable renewable energy output, demand, or both.
  - **Curtailment of renewables**: batteries can store the energy not needed by consumers in hours of high wind and solar output. When non-renewable energy is needed again, batteries can discharge the energy they stored.

U.K.: weekly, monthly and seasonal variability

Analyzing weekly to seasonal issues

Managing longer-term variability

This section explores the longer-term dynamics of a high-renewables system in the U.K., focusing on issues that arise at the ***weekly to seasonal*** horizon.

Challenges

- The main challenge explored in this section is that of long-term resource adequacy. That is, ensuring that demand can be met during longer periods of weeks and months when renewables production may be low due to weather conditions. While these periods are not guaranteed to happen every month or every year, they will certainly occur from time to time and it will be necessary for the power system to be prepared for them.
- For this section, we have again applied five years of past solar/wind production data to each scenario, in order to find the most extreme weeks and months.
- Curtailment is also of interest at the longer-term horizon. There will be long periods of significant wind and solar excess. These may indicate opportunities for long-term storage: if excess energy can be stored for long periods of time and then released, it can help address the resource adequacy problem outlined above.

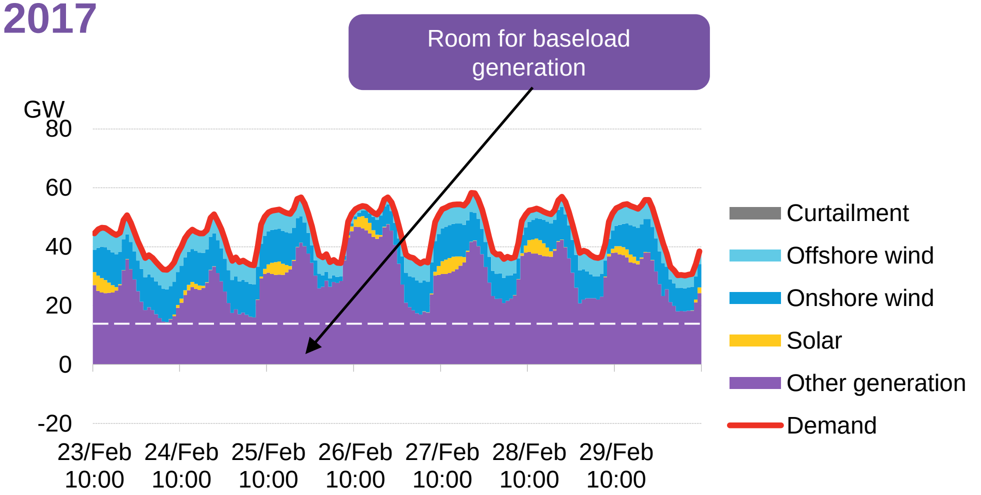
Opportunities

- There is a potential opportunity for future technologies to shift energy over longer periods of time – weeks, months and seasons. This is a significant technical challenge, but could:
  - Reduce the need for back-up capacity. We find that by 2030, the required generating capacity could be reduced by 23% if energy can be shifted across a month instead of just a day. By 2040, generating capacity can be reduced by 9% if energy can be shifted across a quarter instead of a month.
  - Increase the utilization of the remaining back-up assets, as a result of the reduced back-up capacity requirement.
  - Reduce curtailment: by 2040 there will be multiple weeks with more renewable generation than consumption; this will require storing or shifting demand for at least multiple days.
- Batteries and flexible demand technologies are not currently able to shift energy across weeks or months, due to their economics and characteristics. Demand cannot be deferred for weeks, and the sheer scale (and cost) of batteries needed for seasonal storage would be prohibitive.
- Currently, no seasonal storage technologies are economic; but, in future, technologies such as power-to-gas and hydrogen storage may become more cost-effective. Until they are, a full complement of generating capacity is required.
- Still, we find that at about 50% wind and solar penetration (2040), there is not a strong case for seasonal storage, as the benefits to the system of being able to shift energy over longer periods diminish sharply with the length of the period.

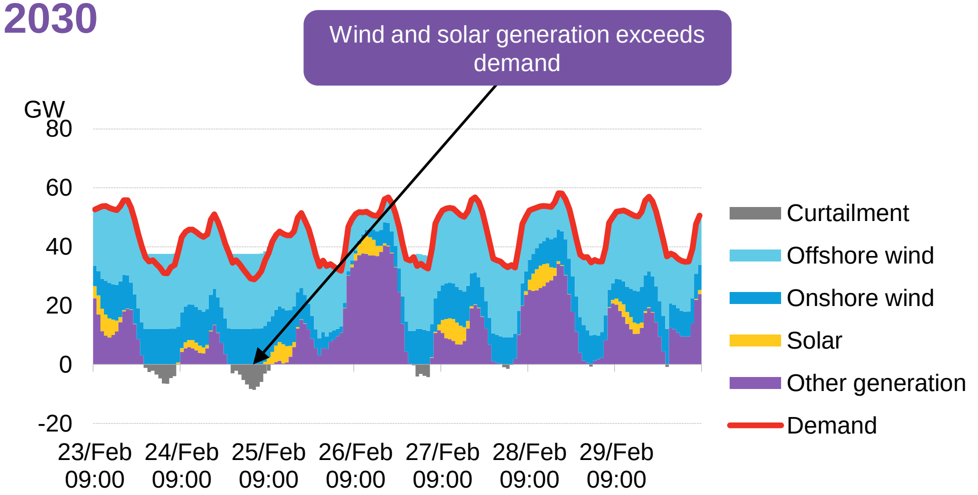
U.K.: weekly, monthly and seasonal variability

Highest wind and solar output week

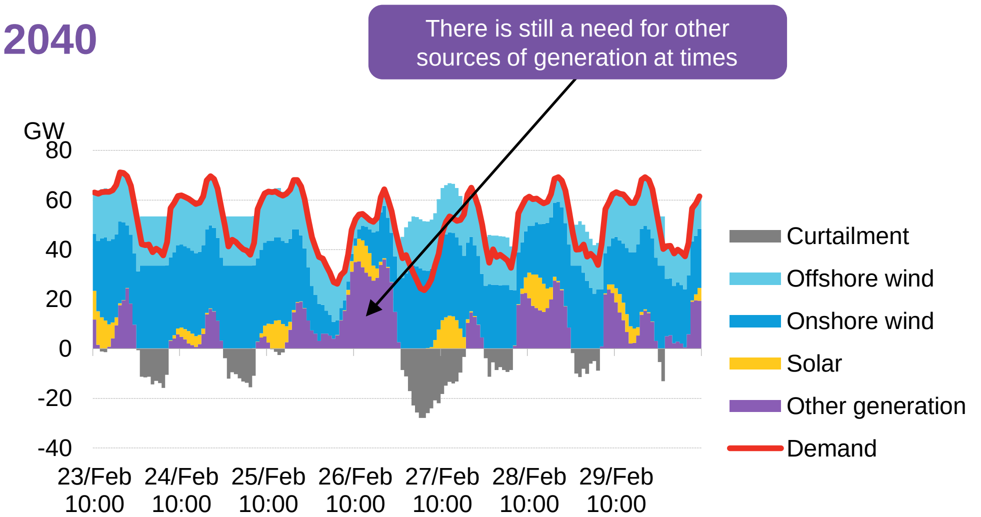
2017



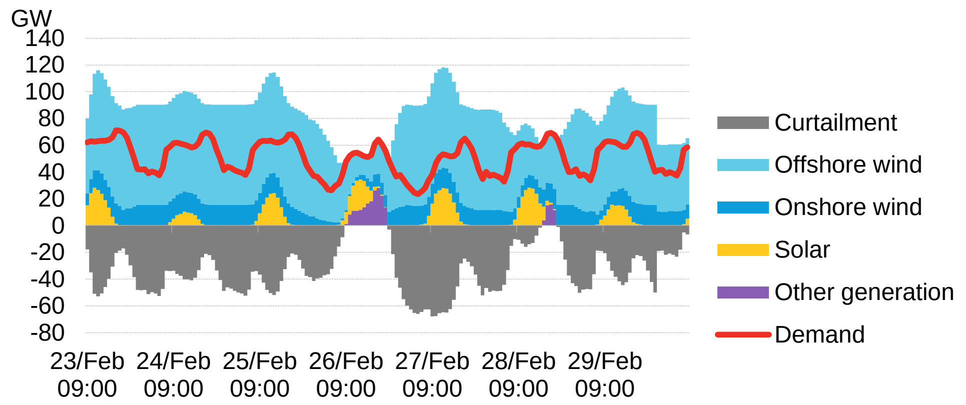
2030



2040



100%



Note: a week is defined as a 168 hour period, not a calendar week.

Highest wind and solar output week

Key trends

The charts above show hourly production and demand for the *highest week (by wind and solar share)* in each scenario. The purple 'other generation' columns show what other energy sources must provide in order to match hourly demand, after wind and solar production are accounted for. Grey shows curtailment, when wind and solar alone exceed demand.

- In all scenarios, the highest week is the same: it occurs in February during a period of high winds.
- In general, the role of other generation diminishes in the later years. However, in 2030 there is still a significant reliance on other generation throughout this highest week of wind and solar production. This is different from the highest individual day (see previous section), where other generation was minimal.
- By 2040, wind and solar production is so great that much less back-up is required in the week. Curtailment is significant throughout the week.

Scenario notes

2017

- In 2017, there a requirement for about 14GW of baseload generation, running flat out at steady output. Even during the periods of highest wind and solar output, there is a minimum level of other generation required.

2030

- By 2030, there are weeks where wind and solar generation exceeds demand at some point every day and accounts for 75% of demand over the period. This leaves no room for technologies that need to run flat-out, such as nuclear power**.**

2040

- However, even in 2040 other sources of generation are still required at times during the highest wind and solar output weeks (though they play a relatively small role, supplying about 16% of electricity). Renewable generation excess is very significant in this week, with 9% of wind and solar output curtailed.

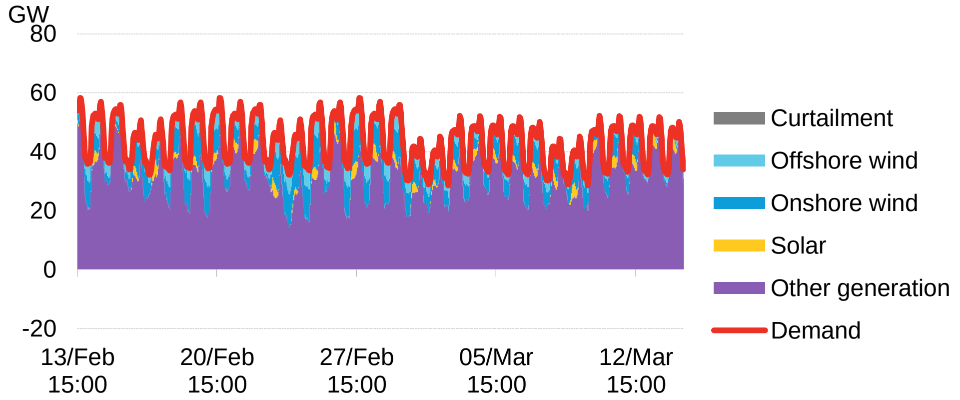
100%

- Although only for a brief period, other resources are needed even in the 100% scenario, and 40% of renewable energy is curtailed in the absence of storage.

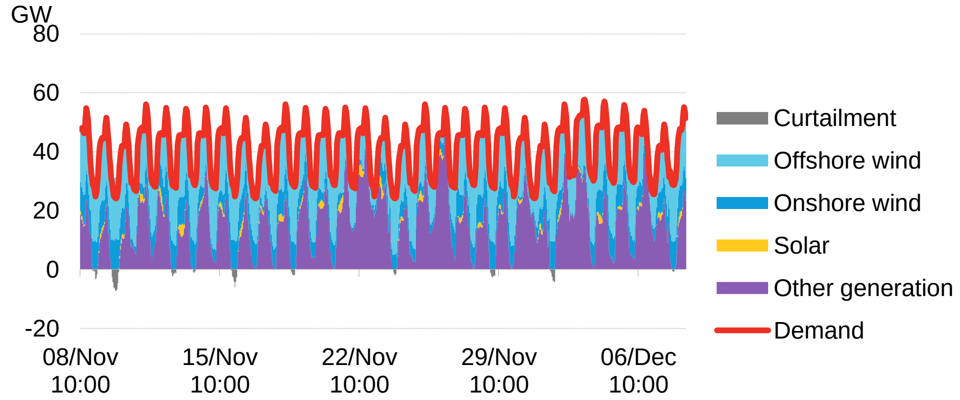
Note: a week is defined as a 168 hour period, not a calendar week.

Highest wind and solar energy output month

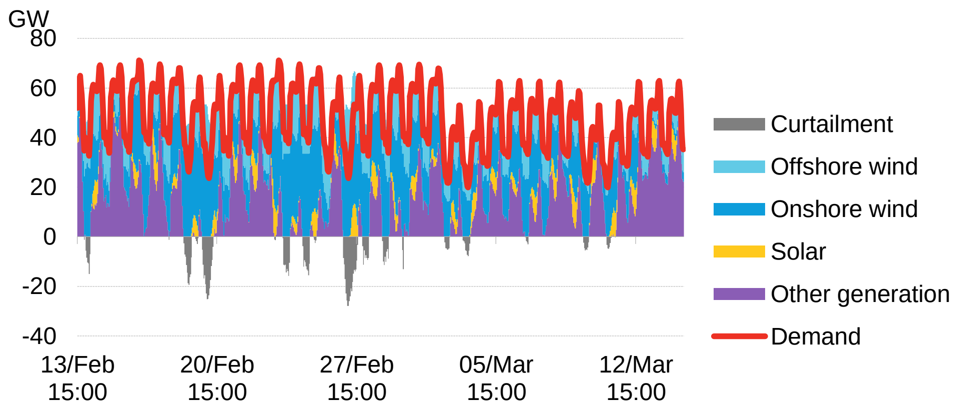
2017



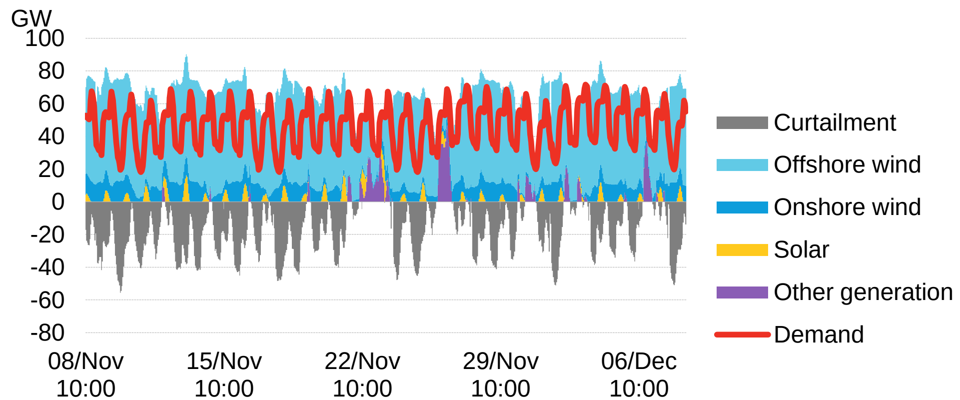
2030



2040



100%



Note: a month is defined as a 730 hour period, not a calendar month.

Highest wind and solar output month

Key trends

The charts above show hourly production and demand for the *highest month (by wind and solar share)* in each scenario. The purple 'other generation' columns show what these energy sources must provide in order to match hourly demand, after wind and solar production are accounted for. Grey shows curtailment, when wind and solar alone exceed demand.

- We see similar trends for high wind/solar output months as we do at the one-week level.
- In these high-production months in 2030 and 2040, wind and solar energy frequently meet most or all of demand. Other generation plays a diminished role, but is still very much needed in all scenarios.
- While there is currently a need for baseload generation, by 2030 there are entire months with no room for generators that are always on.
- By 2040, wind and solar generation more and more frequently surpasses demand, doing so for several significant periods in this high month. In the absence of energy storage or demand shifting, this excess energy is curtailed.

Scenario notes

2017

- As in the ‘weeks’ analysis, in 2017 there a requirement for about 14GW of baseload generation, running flat out at steady output.

2030

- In 2030, wind and solar do not exceed demand every day for a month (unlike in the ‘weeks’ analysis). However, there is clearly little room for baseload generators in this month. There are a few days here and there where some generators could run non-stop, but these periods are relatively short and the energy provision needed (40%) is much lower than in 2017 (60%).

2040

- Other sources of generation are still required at times during the highest wind and solar output months, supplying a third of generation. They still play an important role, but room for baseload is even lower than in 2030.
- There is significant curtailment in the month (5%), but not for the whole period – it is concentrated within a two-week period.

100%

- Other resources are needed for a few hours even in the 100% scenario, though only for short periods. There is a large amount of excess renewable energy across the month, about 29% of wind and solar generation.

Note: a month is defined as a 730 hour period, not a calendar month.

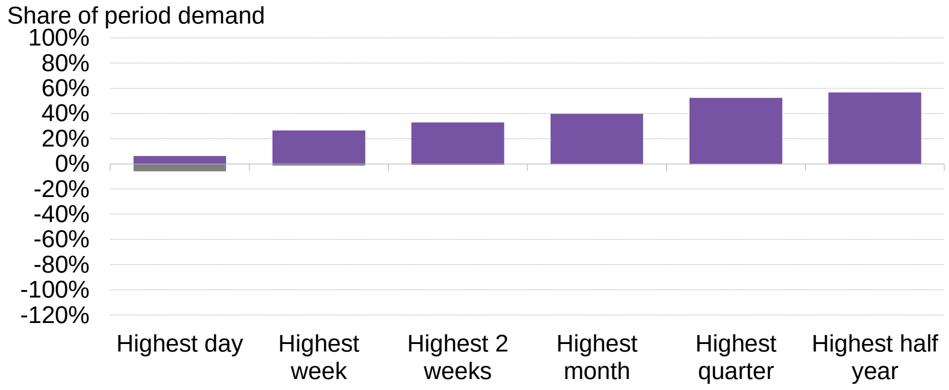
U.K.: weekly, monthly and seasonal variability

Opportunities to shift excess energy during the highest wind and solar output periods

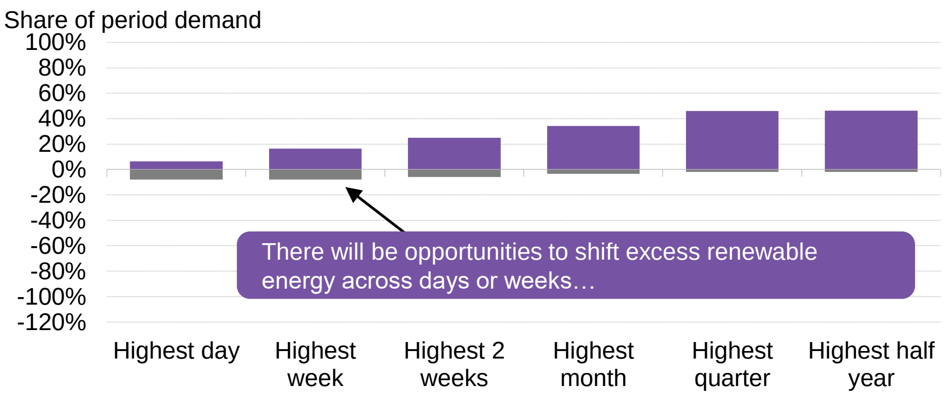
Share of demand met by other resources, and share of curtailment, in highest-wind/solar periods (days, weeks, etc.)

2017

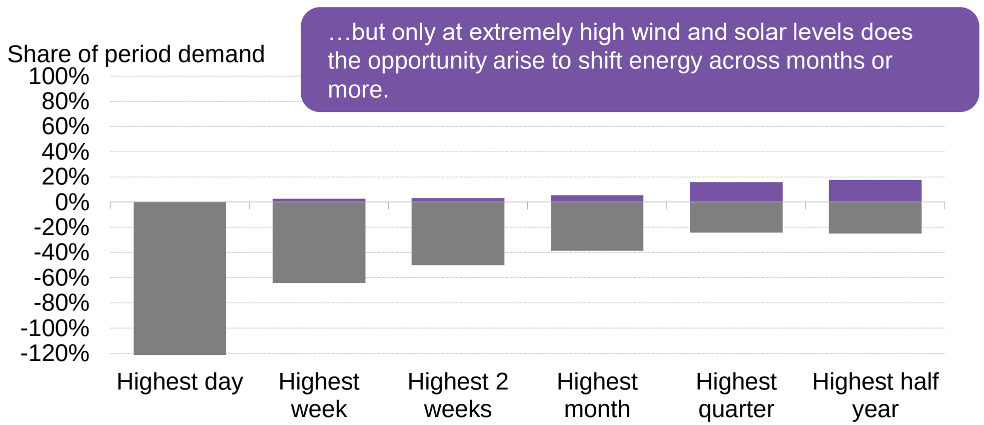
2030



2040



100%



■ Non wind and solar generation ■ Curtailment

Opportunities to shift excess energy during the highest wind and solar output periods

Key trends

The charts above show, only for the *highest* wind/solar output periods (days, weeks, months etc) in each scenario, how much of demand is met by other generation and how much renewable energy is curtailed.

- Clearly, as more wind and solar are added, these periods see less and less demand being met by other resources, and more curtailment. This is evidenced by all the columns moving lower (and grey negative areas appearing) as we progress through the scenarios.
- Where we see columns that show both purple and grey, this indicates that there is both excess renewable energy and a need for back-up within the same high-output period. This implies an opportunity to store excess renewable energy and release within that same period.
- This starts to occur in 2030 at the day level – ie, there is opportunity to shift energy within days in 2030.
- In 2040, we see this opportunity at the week, 2-week and even month level. However, curtailment at the quarter- and half-level (ie, seasonal level) is not large enough relative to the need for back-up, to be worthwhile storing and shifting.
- Only in the extreme 100% scenario, can energy shifting at the multi-month level start to make sense.

Scenario notes

2017

- There is no curtailment even in these highest periods, so there is no opportunity to shift excess energy.

2030

- On the highest wind/solar day, only about 6% of demand is met by other sources, and a similarly small amount of renewable energy is curtailed. This indicates opportunity to store and shift that surplus energy to meet the demand (removing the need for back-up on that day).

2040

- The highest-wind/solar day and week each see curtailment (8%) that is of a similar order of magnitude to the net demand that needs to be met by back-up resource (6-16%). This indicates opportunity to store and shift energy within these longer periods.
- However, there is little opportunity to shift energy across longer periods.

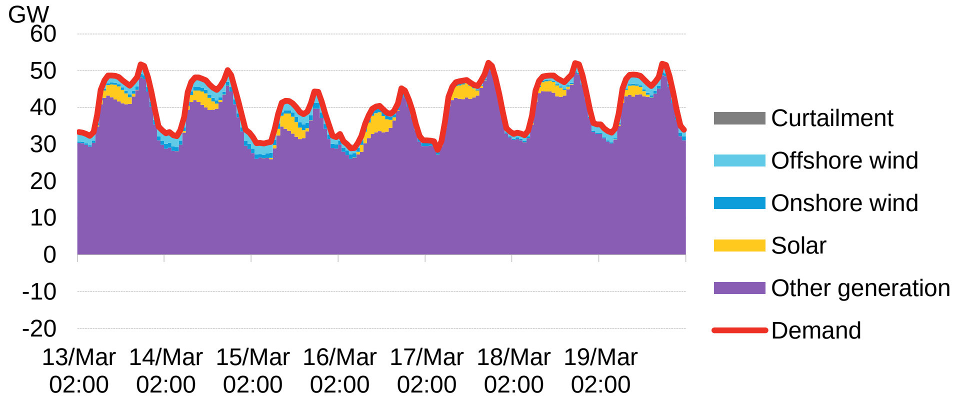
100%

- In this extreme case, there is an opportunity to do large-scale seasonal storage, shifting energy across months and even across seasons.

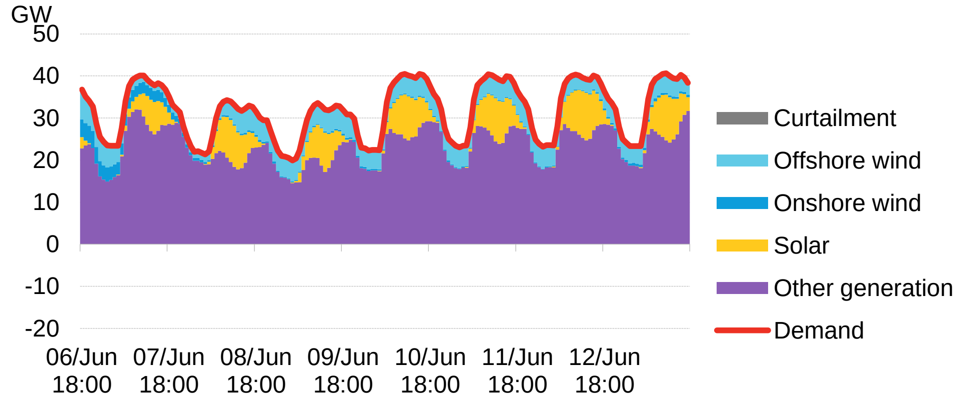
U.K.: weekly, monthly and seasonal variability

Lowest wind and solar energy output week

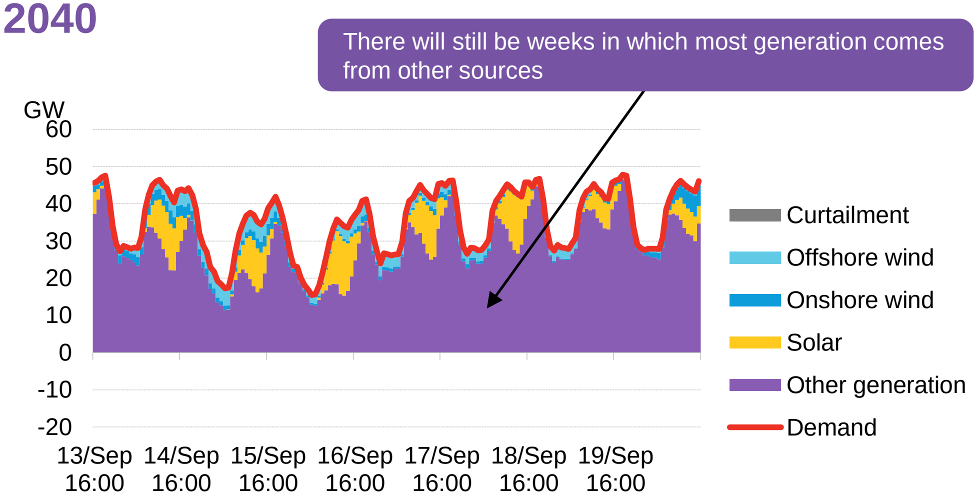
2017



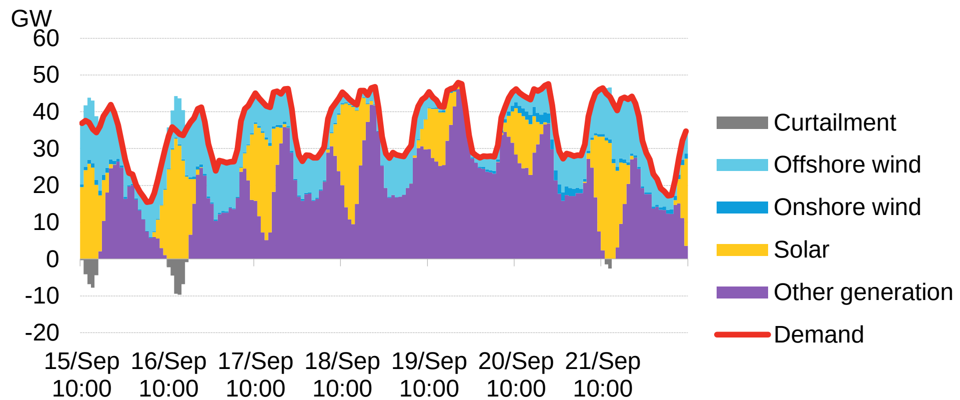
2030



2040



100%



Note: a week is defined as a 168 hour period, not a calendar week.

Lowest wind and solar energy output week

Key trends

The charts above show hourly production and demand for the *lowest week (by wind and solar share)* in each scenario. The purple 'other generation' columns show what other energy sources must provide in order to match hourly demand, after wind and solar production are accounted for. Grey shows curtailment, when wind and solar alone exceed demand.

- In the U.K., minimum renewables generation happens during wind-still periods, as the bulk of variable green energy output comes from wind.
- Across all scenarios, there are weeks when most generation has to come from other sources. These weeks see little variable renewable energy generation and require substantial back-up capacity.
- Low wind and solar weeks require about 80% of generation from other sources, even by 2040. Unlike the highest weeks and months of wind and solar generation, these low weeks do have room for baseload resources to run throughout the period.

Scenario notes

2017

- 80% of demand is met by non-wind/solar generators in this low week.

2030

- Despite the growth in wind and solar capacity, the lowest week in 2030 still sees 73% of demand met by other generators.
- On average, 23GW of other generation are online during this period.

2040

- Even in 2040, the lowest week still sees 80% of demand met by non-wind/solar generation.
- On average, 28GW of other generation are online during this week.
- The figures for 2040 are higher than in 2030 due to a change in the wind and solar mix (less offshore wind and more solar) and the added demand from electric vehicles.

100%

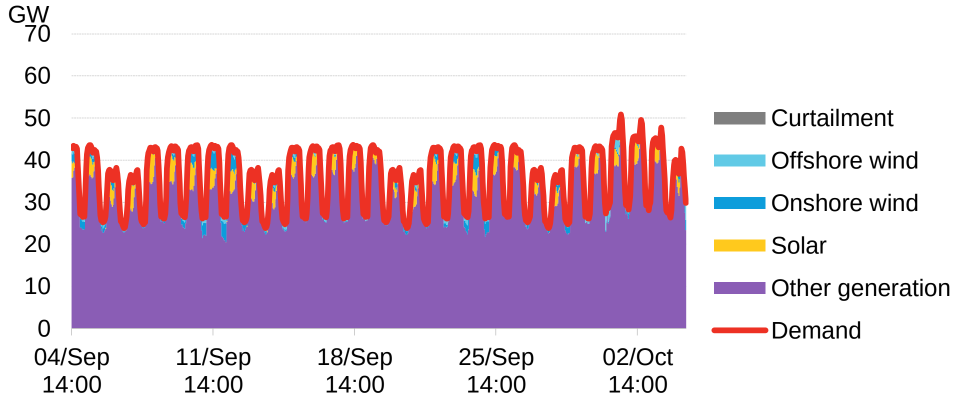
- Even in this scenario, where there is enough wind and solar to supply annual power demand, there are weeks when other sources must meet as much as 54% of demand.

Note: a week is defined as a 168 hour period, not a calendar week.

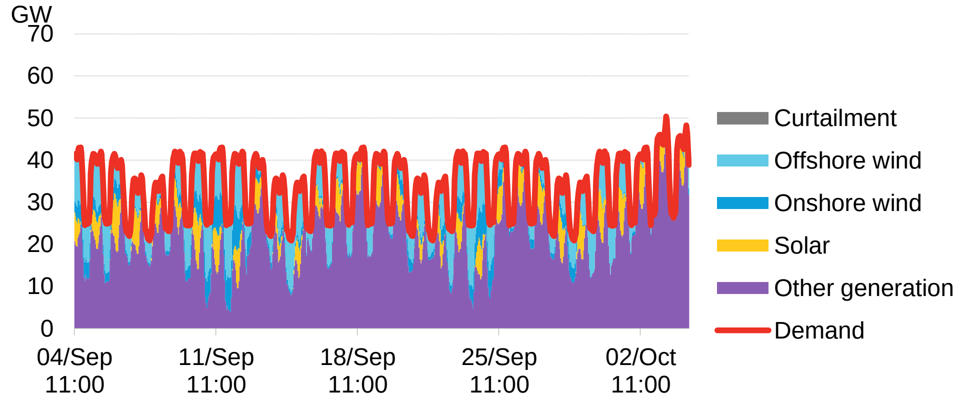
U.K.: weekly, monthly and seasonal variability

Lowest wind and solar energy output month

2017

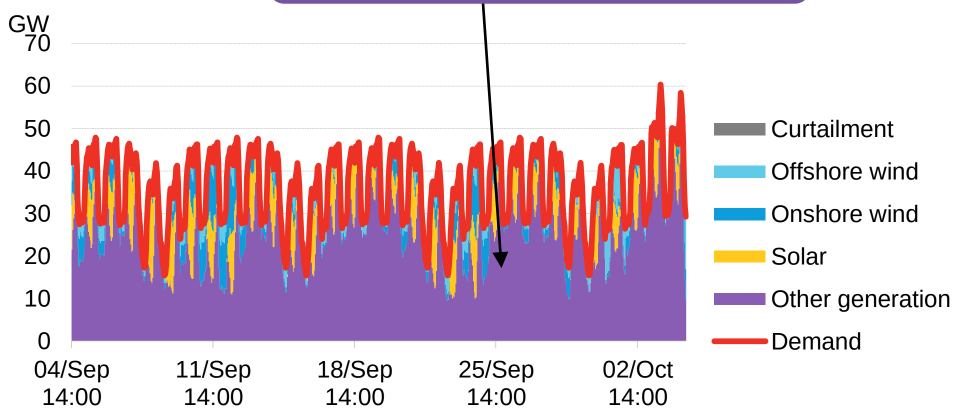


2030

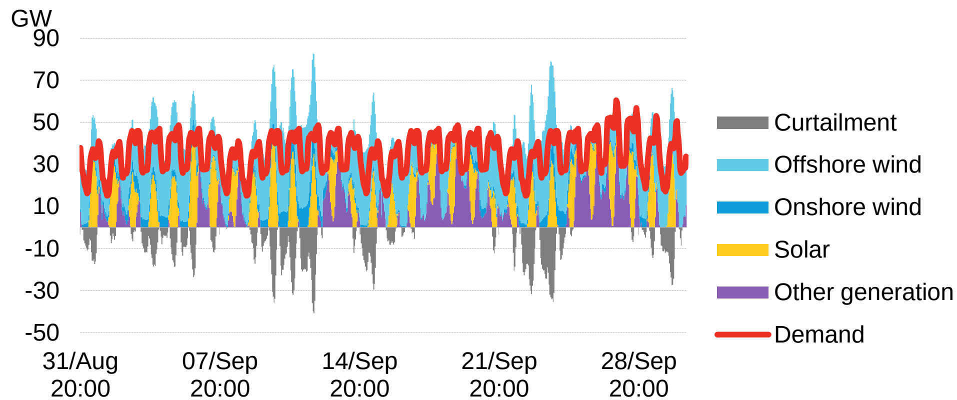


2040

There will be entire months without excess renewable generation (curtailment)



100%



Note: a month is defined as a 730 hour period, not a calendar month.

Lowest wind and solar output month

Key trends

The charts above show hourly production and demand for the *lowest month (by wind and solar share)* in each scenario. The purple 'other generation' columns show what other energy sources must provide in order to match hourly demand, after wind and solar production are accounted for. Grey shows curtailment, when wind and solar alone exceed demand.

- Low wind and solar output periods can last for whole months, not just weeks at a time. Here we see month-long periods in September where wind and solar production remain low.
- The amount of generation required from other sources falls from 90% to about 70% from 2017 to 2030, but does not fall significantly thereafter. Around 70% of generation has to come from other sources in 2030 and 2040 during low wind and solar output months.

Scenario notes

2017

- 90% of demand is met by non-wind/solar generators across this month-long period of low renewables output.

2030

- By 2030, low-renewables months need less support from other generators: the latter supply 66% of demand.
- On average, 22GW of other generation are online during this period, but they need to be flexible to adjust to changes in renewables production and demand.

2040

- In the low-wind/solar month in 2040, other sources still need to supply around 72% of demand.
- On average, 26GW of other generation are online during this week, and as in 2030 they need to be flexible.
- The figures for 2040 are higher than in 2030 due to a change in the wind and solar mix (less offshore wind and more solar) and the added demand from electric vehicles.

100%

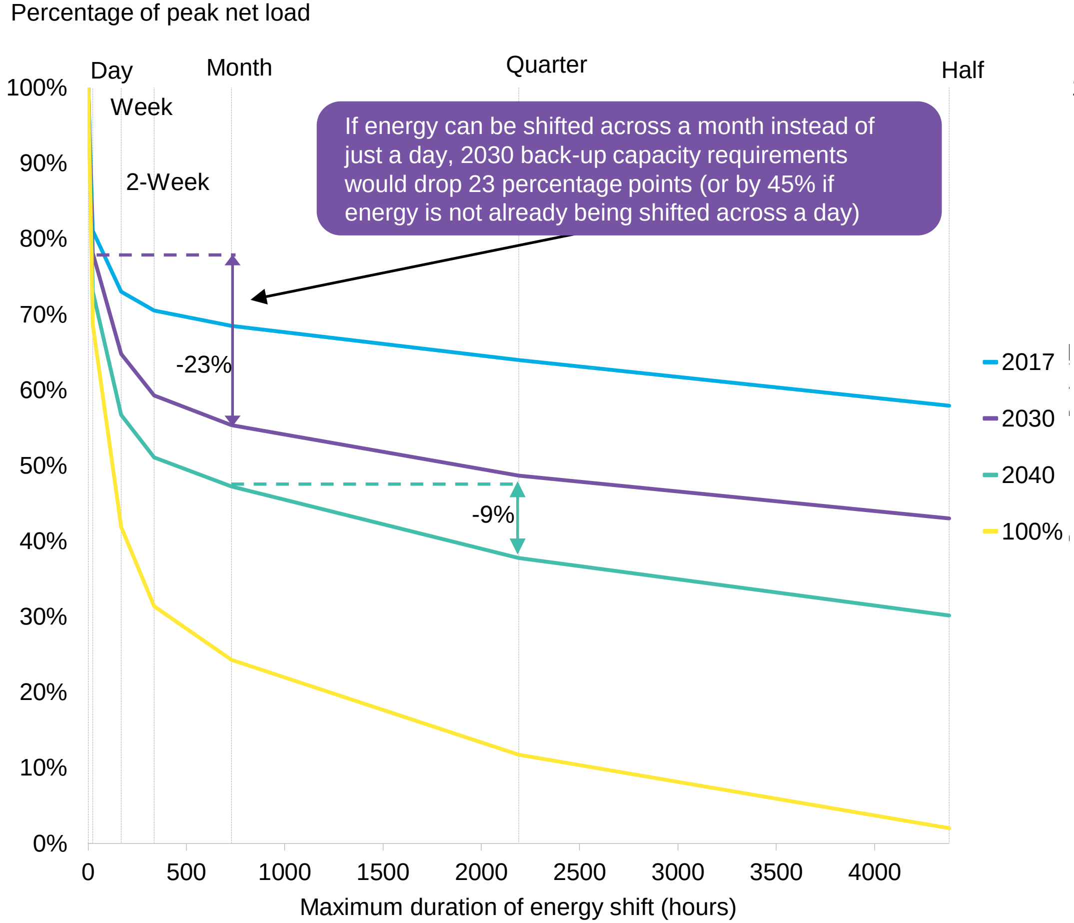
- In this scenario, even low-renewable energy months see instances of excess renewable energy. The net load curve becomes highly volatile on a daily basis due to increased solar generation. Daily storage could help mitigate these swings.

Note: a month is defined as a 730 hour period, not a calendar month.

U.K.: weekly, monthly and seasonal variability

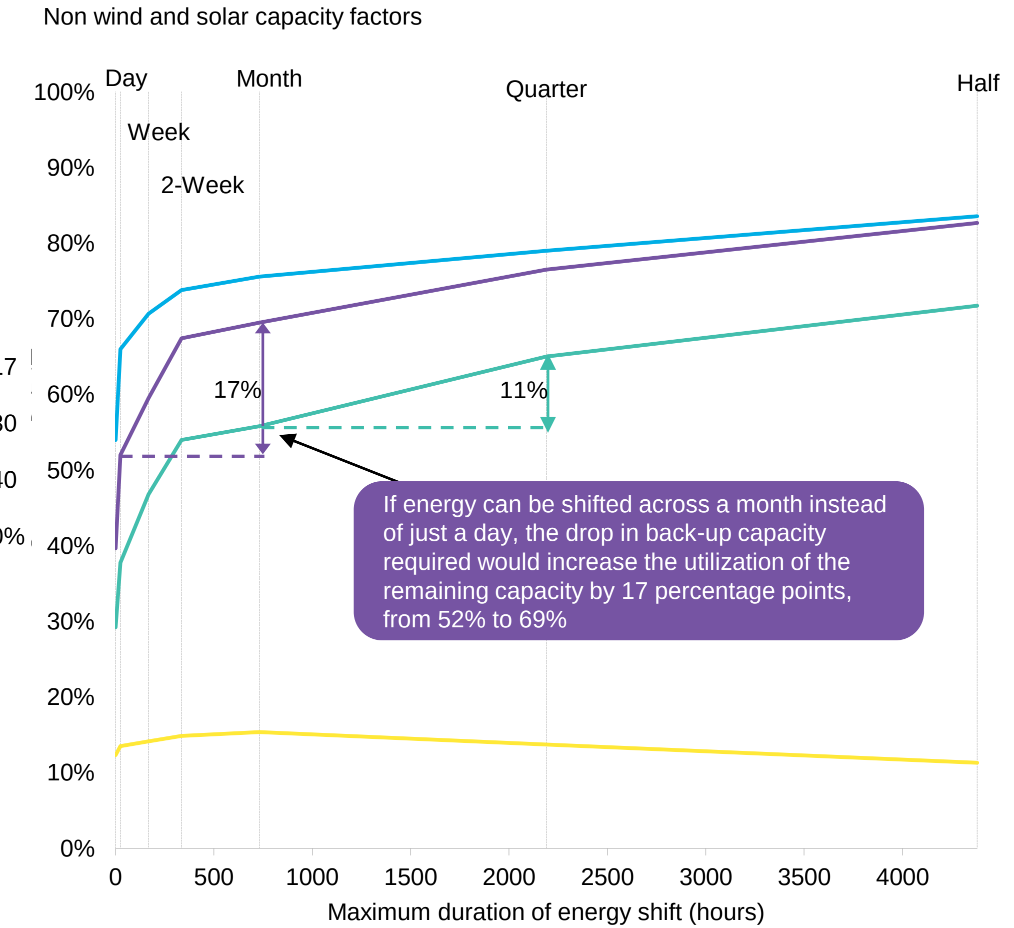
Opportunities for long-term energy shifting

Opportunity to reduce back-up generating capacity



Source: Bloomberg New Energy Finance

Opportunity to increase non wind and solar capacity utilisation



Source: Bloomberg New Energy Finance

Opportunities for long-term energy shifting

Energy shifting to reduce back-up requirement

- As illustrated in previous slides, back-up is needed to meet both short-term peaks (hours, days) and longer periods of low renewable production (weeks, months).
- The left-hand chart above explores what duration of energy shifting / storage would be required to take away the need for back-up generation. The highest peaks – i.e. hours when almost all peak load has to be met with back-up capacity – can be reduced using short-duration storage. As the length of the period over which energy is shifted increases, so does the amount of energy that needs to be stored.
- However, these short, high peaks only account for a small amount of back-up capacity. To reduce back-up capacity considerably, longer storage / shifting is needed. For example, in 2017, an energy shift of a couple of hours is enough to reduce required back-up capacity by 19%, but to reduce it by 27% requires the ability to shift energy for up to 24 hours.

Increasing back-up utilization

- The right-hand chart above illustrates the impact that longer storage durations could have on back-up utilization. As discussed previously, higher penetration of wind and solar lead to lower utilization of back-up generation. (This can be seen in the chart: the lines are lower for higher wind/solar scenarios). This has the effect of hurting the economics of conventional generators, reducing their operating hours and increasing their costs.
- If energy shifting / storage can reduce back-up capacity requirements, this will have the effect of improving utilization – and economics – of the remaining back-up generators.
- For example, in 2017, adding hourly storage could improve capacity utilization from 54% to 66%. One week's duration of storage would improve it to 73%.

Scenario notes

2030

- In 2030, being able to shift energy across a *day* reduces back-up capacity by 22%, increasing utilization from 40% to 52%.
- Being able to shift energy across a *month* could reduce back-up capacity by a further 23 percentage points to 55%, increasing back-up capacity utilization further to 69%

2040

- In 2040, being able to shift energy across a *day* reduces back-up capacity by 27%, increasing utilization from 29% to 38%.
- Being able to shift energy across a *month* could reduce back-up capacity by a further 25 percentage points to 47%, increasing back-up capacity utilization by further to 56%
- Being able to shift energy across a *quarter* could see an additional 9% of non-wind/solar generation assets become redundant. This would increase back-up capacity utilization to 65%.

Germany: overview of scenarios and issues

Analysis of a high-renewables power system in Germany

Overview of issues

This section summarises some of the core issues that arise in a high-wind/solar future for Germany.

We explore four main issues:

1. Wind and solar energy exceeds demand at times

- Wind and solar generation respond to weather conditions that are independent of demand. As a result, there is a mismatch between variable renewable generation and demand.
- Initially, wind and solar generation exceeds demand when periods of high output coincide with periods of low demand (e.g. overnight or during a sunny weekend).
- As more wind and solar capacity comes online, variable renewable generation exceeds demand more frequently, sometimes even during periods of high demand.

2. Significant back-up capacity is still required

- Regardless of the level of wind and solar capacity installed, moments with very low-to-no wind/solar output persist.
- Spikes in demand that coincide with a still, cloudy period mean that other generators are required to fill the gap.

3. The utilization of back-up capacity declines

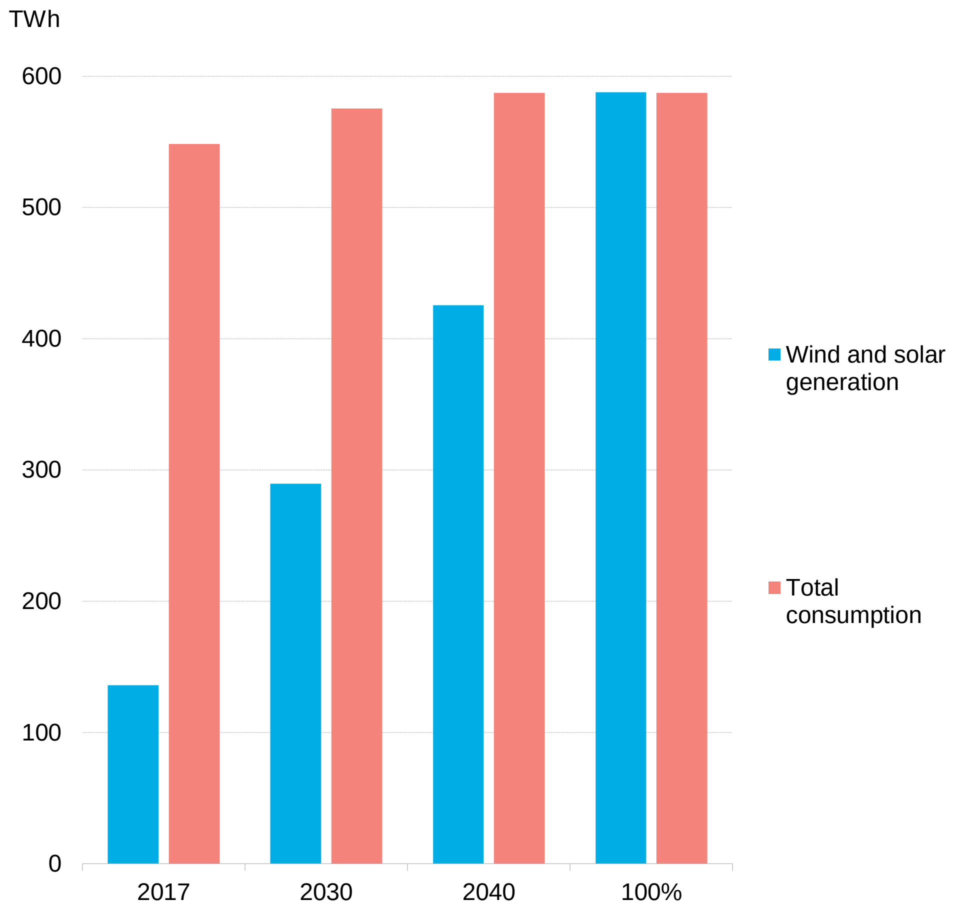
- Energy from wind and solar meets an ever-greater share of demand, reducing the energy required from other sources.
- This results in decreasing utilization of back-up capacity rather than plant closures, since these assets are still required to meet demand during periods of low wind and solar generation.

4. System volatility increases

- Historically, flexible generation sources were only required to adjust their output to match demand fluctuations. As wind and solar generation increases, these resources will need to adjust their output according to both demand and variable renewables.
- At very high penetration rates for wind and solar, such generating sources also need to cope with shutting down and starting up over short time intervals.

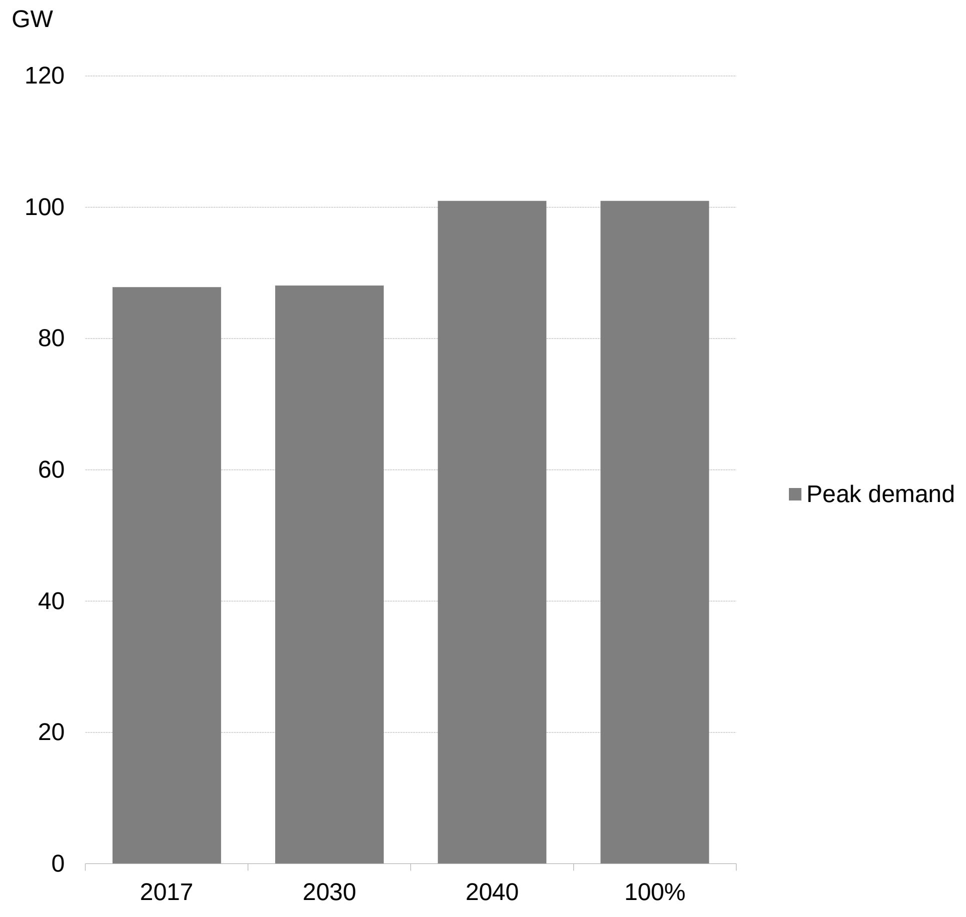
Four scenarios used in this analysis

Annual generation



Source: Bloomberg New Energy Finance

Peak demand



Source: Bloomberg New Energy Finance

Four scenarios used in this analysis

About the scenarios

- For our analysis of the German flexibility gap, we looked at four scenarios* for wind and solar penetration, which we labelled:
  1. 2017
  2. 2030
  3. 2040
  4. 100%
- The first three scenarios (2017, 2030 and 2040) model a German system with wind and solar penetration equivalent to these respective years in the BNEF New Energy Outlook forecast.
  – These scenarios explore what the flexibility gap would look like for Germany, if the renewables deployment modelled in the New Energy Outlook was to come true.
  – The remainder of the generation stack (non-wind and solar) is simplified to a single resource that we call 'other generation'.
- In the fourth scenario, ‘100%’, wind and solar generation per year is equivalent to annual electricity demand.
  – Demand is not met in every hour, so other resources or storage are still needed.
  – This is not an economically-modeled scenario along the lines of the 2017, 2030 and 2040 scenarios, which are outcomes from the New Energy Outlook. It is only included to illustrate an extreme case.

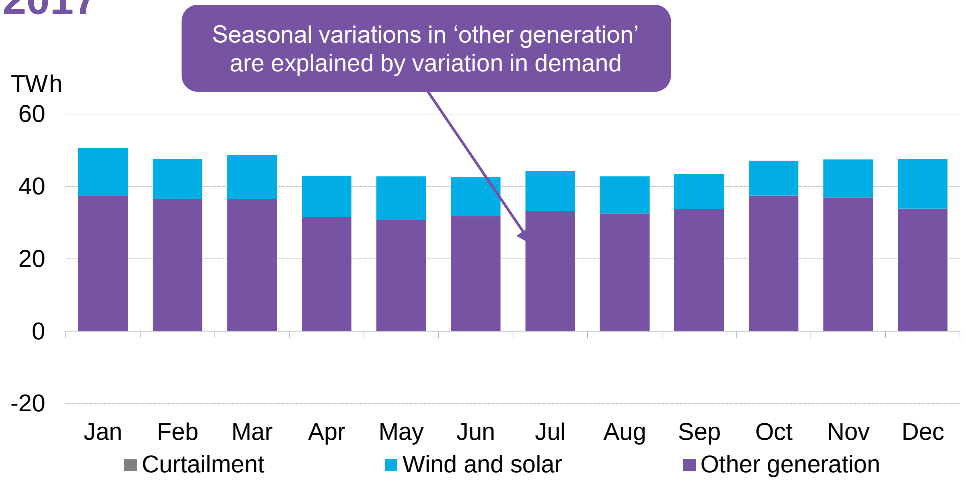
Note: we use ‘scenarios’ here to mean future penetration of wind/solar – not alternative trajectories for the energy system. They are different points on the same trajectory.

Key figures used in each scenario

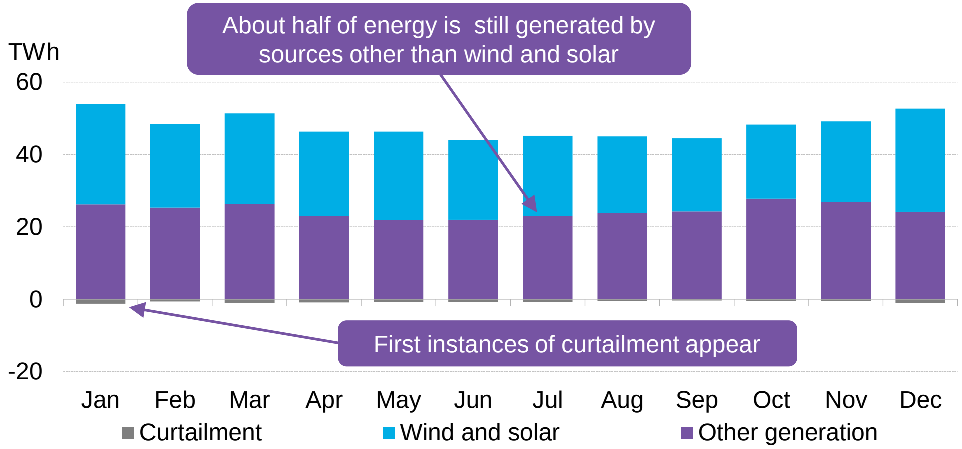
Scenario	2017	2030	2040	100%
Total demand (TWh)	548	575	589	589
Peak demand (GW)	88	88	101	101
Share of demand met by wind and solar (%)	25%	49%	61%	75%
Curtailment (TWh)	0	14	60	145
Onshore wind capacity (GW)	51	65	62	48
Offshore wind capacity (GW)	5	15	13	65
Solar PV capacity (GW)	42	81	150	138

Monthly generation

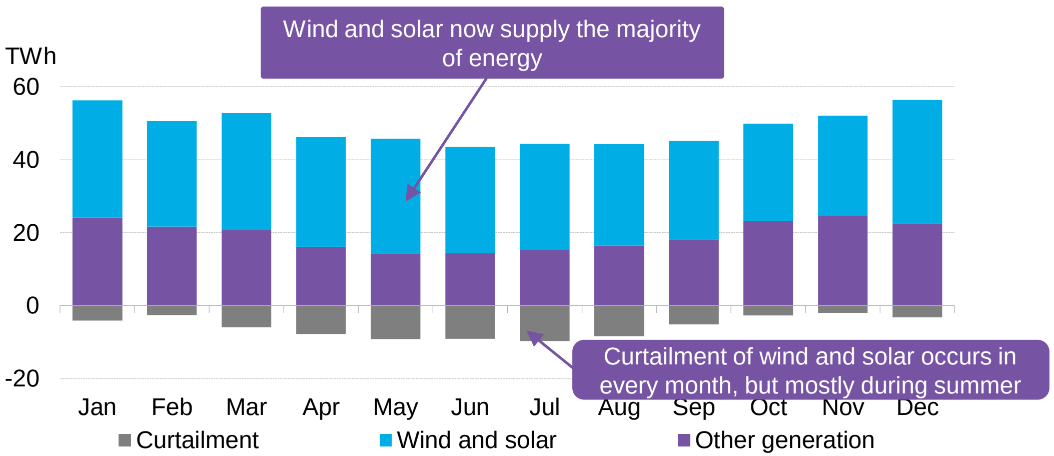
2017



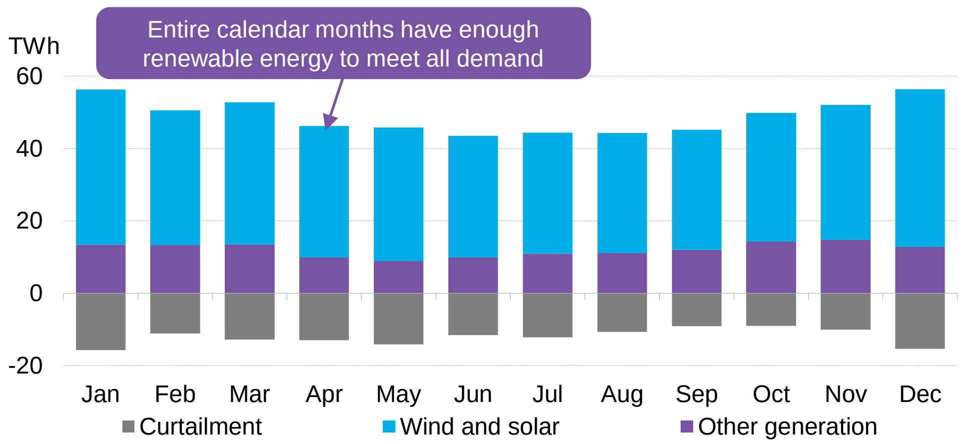
2030



2040



100%



Note: other generation includes all form of generation besides wind and solar, and can also be interpreted as 'net demand' – total demand net of wind and solar generation.

Monthly generation

Key trends

The charts above show how much of demand is supplied by wind/solar or other resources, at ***monthly*** granularity, for each scenario.

Two dynamics are apparent in the charts:

- **Decreasing 'other' generation:** non-wind/solar generation accounts for 75% of energy demand in 2017, but this falls to 51% in 2030, and 39% by 2040.
  - However, even in the extreme scenario, where wind and solar generate megawatt-hours equivalent to 100% of demand, 'other' sources are still needed to provide 25% of electricity. This is because of the mismatch between wind and solar generation and demand.
- **Increasing curtailment (wasting) of wind and solar energy:** In the absence of energy storage or demand shifting, the wasting of variable renewable energy – because of generation exceeding demand – grows from none in 2017, to 14TWh in 2030, and 60TWh in 2040. These figures are calculated based on an assumption that none of this 'spare' electricity goes into some sort of storage.
  - However, excess renewable output never grows so large that it needs to be shifted from one month to the next. This only happens in the 100% scenario.

Scenario notes

2017

- With low wind and solar penetration, their seasonality has a limited effect on the system. Instead, demand seasonality – high in winter, low in summer – explains most of the variability in the output of other generators.

2030

- Despite the growth in the share of variable renewables, other generators are still needed to meet about half of demand.
- The first occurrences of wind and solar curtailment show that even at medium penetration levels, over-generation is an issue.

2040

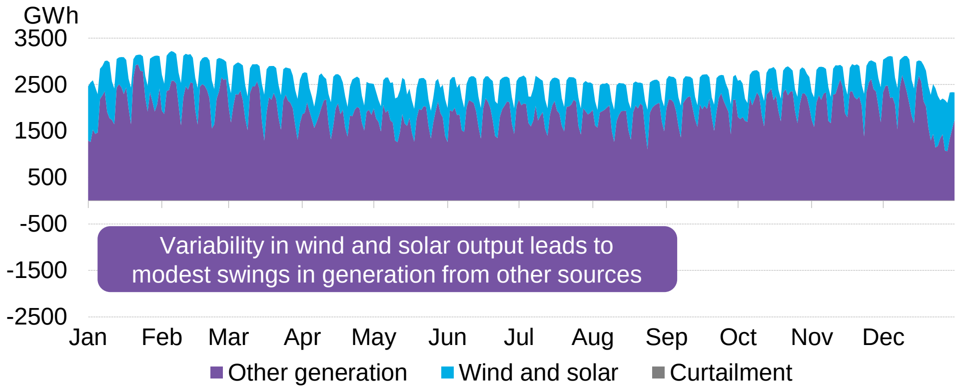
- Wind and solar output grows to supply 60% of annual electricity, and become the largest source during every month. Other generators focus on providing back-up capacity.
- Curtailment is a significant issue that happens every month, especially in summer when demand is low and solar output high.

100%

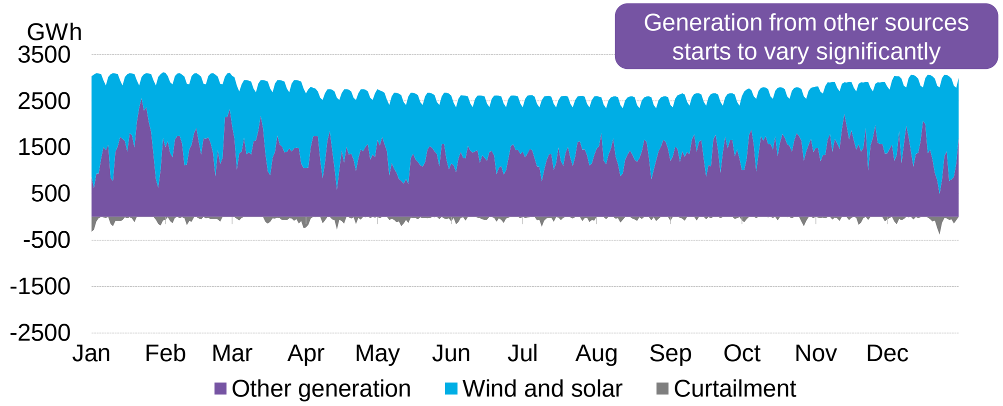
- Because wind and solar output does not always match demand, back-up generation is still needed – even though output by the former two is as high as annual electricity demand.
- In some months, variable renewables generate more energy than is demanded. This is where being able to shift output from one month to another becomes useful.

Daily generation

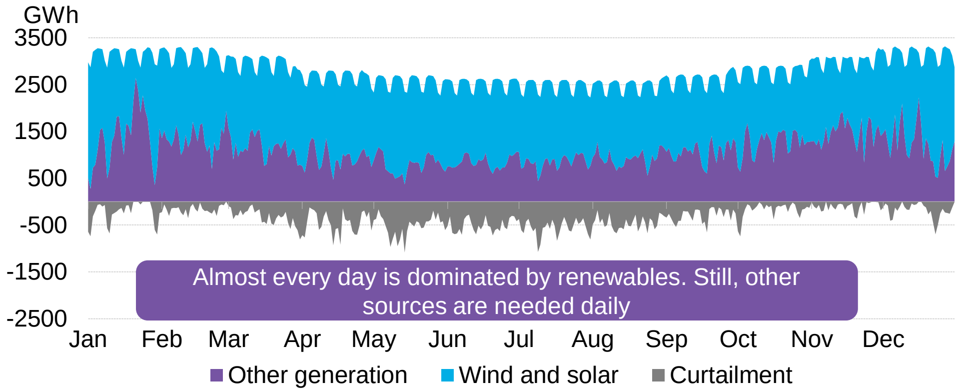
2017



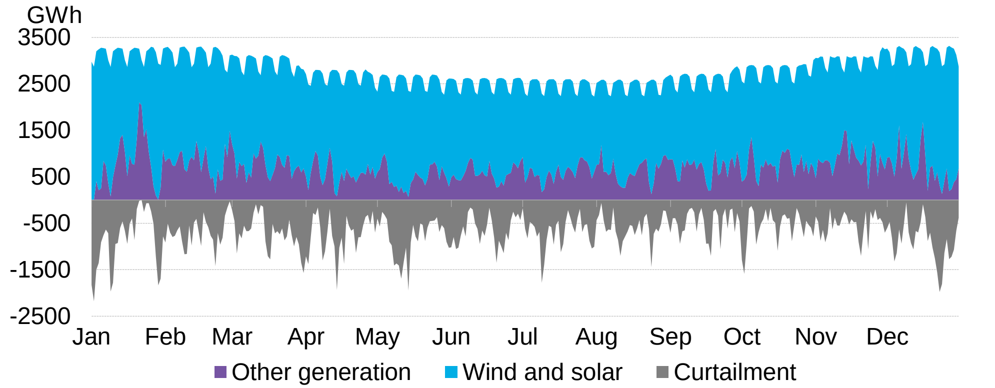
2030



2040



100%



Daily generation

Key trends

The charts above show how much of demand is supplied by wind/solar or other resources, at ***daily*** granularity, for each scenario.

Looking at the daily curve reveals a more detailed picture. The two main dynamics are:

- **Growing variability:** the magnitude of fluctuations in solar and wind output grows considerably from 2017 to 2030. As a result, ‘other’ generation output also experiences increasing levels of volatility.
- **There are still low (near-zero) wind and solar days**, even at high shares of renewables in 2040, requiring other sources to step in.
  - This is markedly different from the monthly charts shown previously, where every month has significant wind and solar generation. At the daily level, there is much more variation.

Scenario notes

2017

- Swings in variable renewable output on consecutive days can be as high as 103%. A wind-still/cloudy day, followed by a windy/sunny one explain the most extreme of swings.
- The penetration of wind and solar is still low. As a result, variable renewables never get close to exceeding daily demand.

2030

- More wind and solar means a more volatile system. The effects of insolation or wind speed changes are amplified by the capacity installed.
- As a result, in the course of 24 hours, total back-up generation might be required to vary its output by up to 92%.

2040

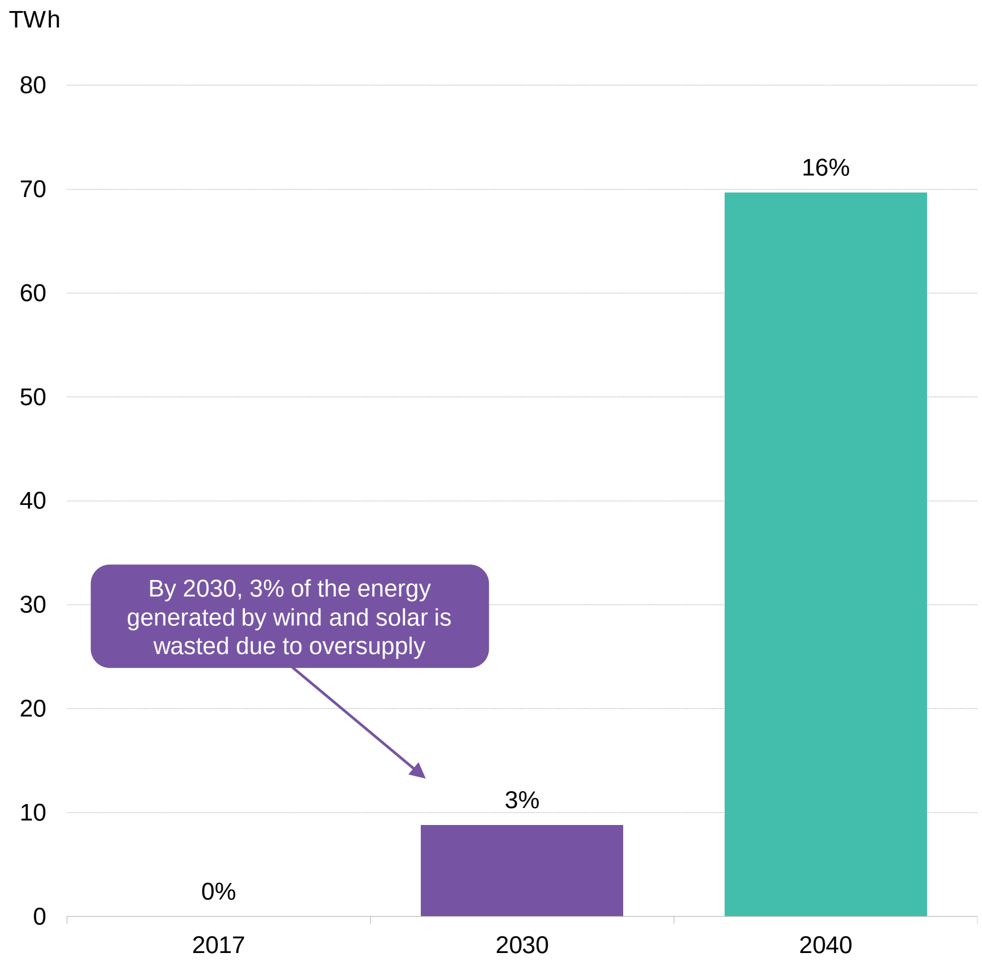
- Other generators see large swings in their output, and utilization. There are occasions when variable renewable output is so high that back-up plants only provide 10% of the daily energy. On low wind and solar days, their share grows to 81% of daily energy.
- Germany’s high PV capacity results in higher summer curtailment.

100%

- With wind and solar able to provide as much energy as needed, other generators become a purely back-up option. Yet, even in this scenario, there are days when other sources are required to supply more than 68% of daily energy needs.

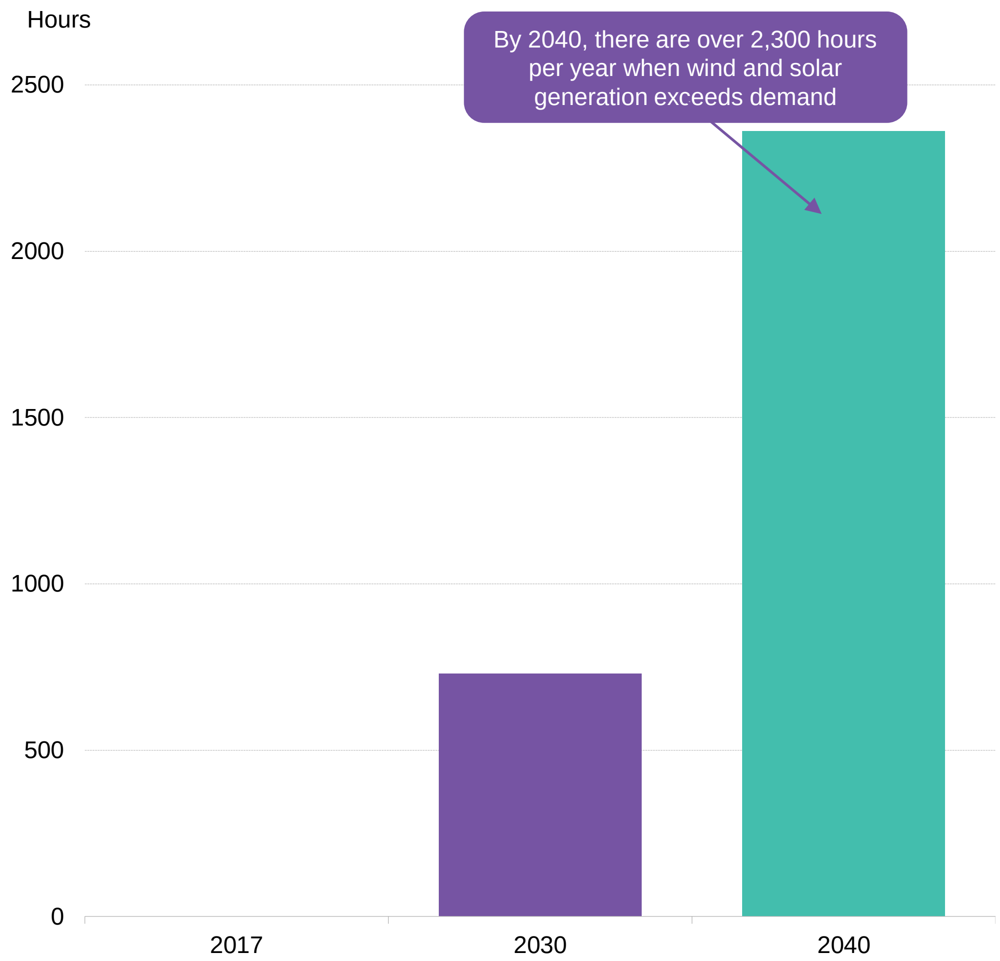
Curtailment of wind and solar generation

Wind and solar energy curtailed by scenario



Source: Bloomberg New Energy Finance

Hours of wind and solar curtailment by scenario



Source: Bloomberg New Energy Finance

Curtailment of wind and solar generation

Key trends

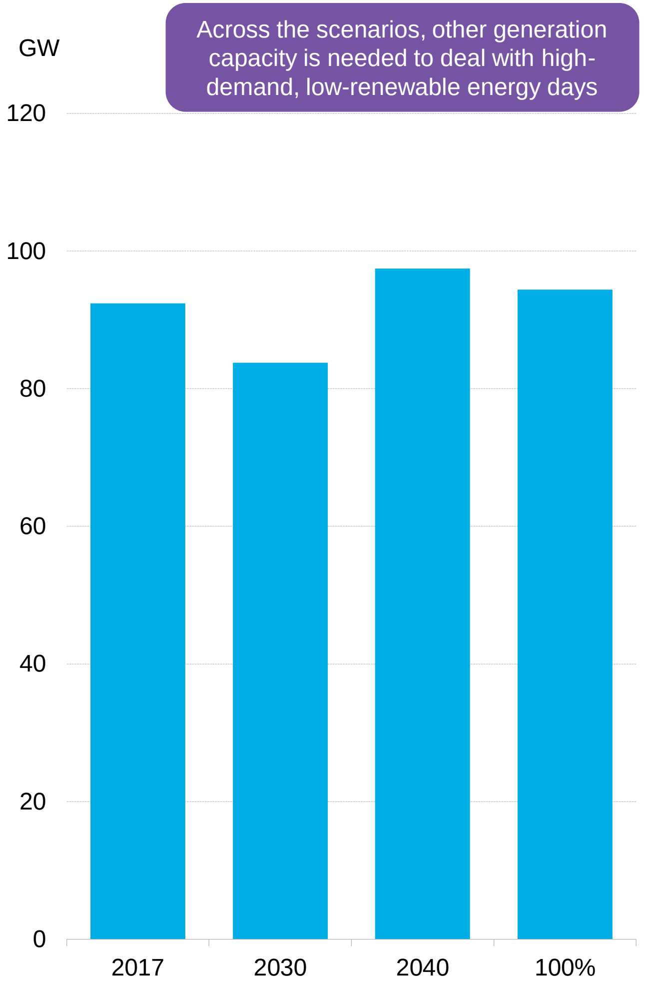
- **Curtailment of wind and solar becomes increasingly common** as penetration rises. This happens when more wind and solar power is generated than is required at that point in time.
- **By 2040, about one seventh of energy generated from solar and wind is curtailed**, with a lot of curtailment taking place in summer as Germany's high PV capacity saturates the system. However, these curtailment figures could be higher still, as other system constraints can lead to the wasting of green energy. These constraints include:
  - Shortfall of transmission capacity to transport solar / wind energy to demand centers.
  - Inflexibility of other parts of the energy system, making renewable curtailment the cheapest option for balancing.
- **Curtailment represents an opportunity for technologies that can store or shift energy**
  - These include batteries and other energy storage technologies (shifting supply), or demand-side response and dynamically-charging electric vehicles (shifting demand).
  - Interconnectors can also play a significant role, to enable export of renewable energy at times of surplus.

Scenario notes

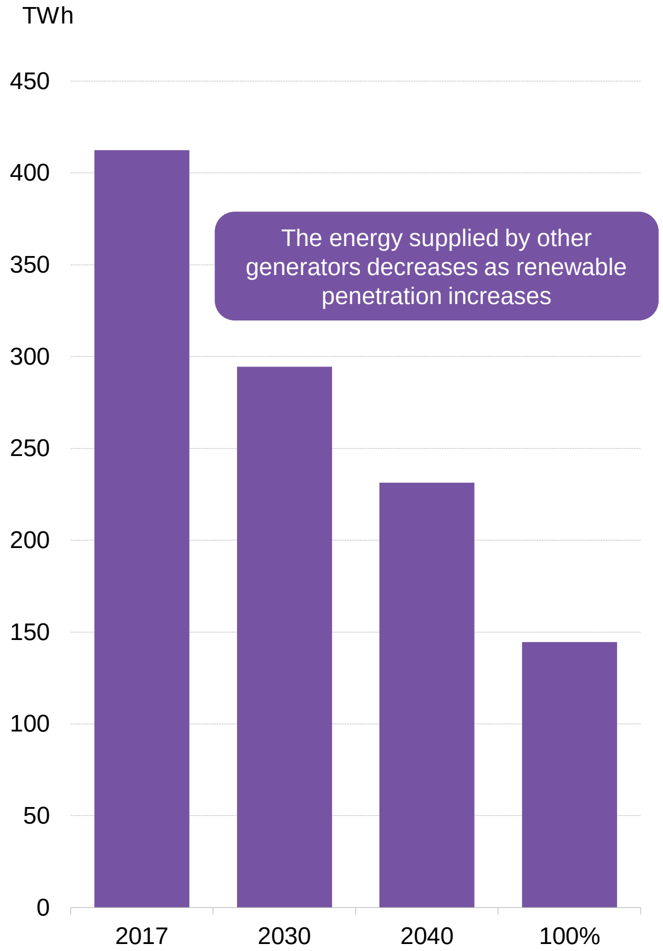
- **By 2030, about 3% of wind and solar output is wasted**
  - Curtailment occurs during 730 hours, or for about a month.
- **By 2040, curtailment jumps to 16%** of total energy supplied by renewables
  - There are over 2,300 hours when renewable output exceeds demand – equivalent to about a quarter of the year.

Back-up capacity & declining utilisation

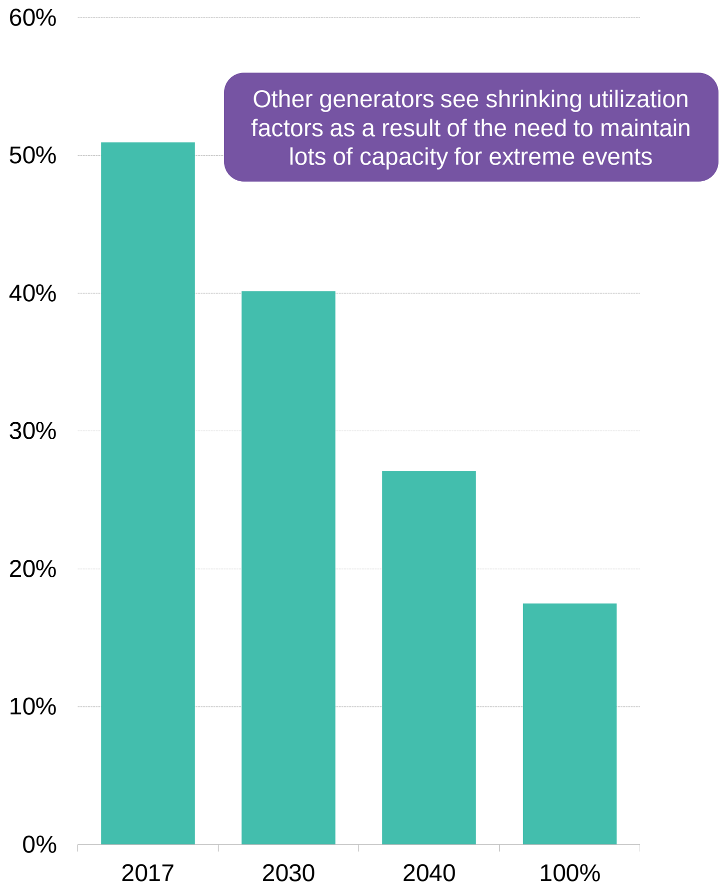
Peak output of 'other generators'



Energy generated by 'other generators'



Utilisation of 'other generators'



Back-up capacity & declining utilization

Key trends

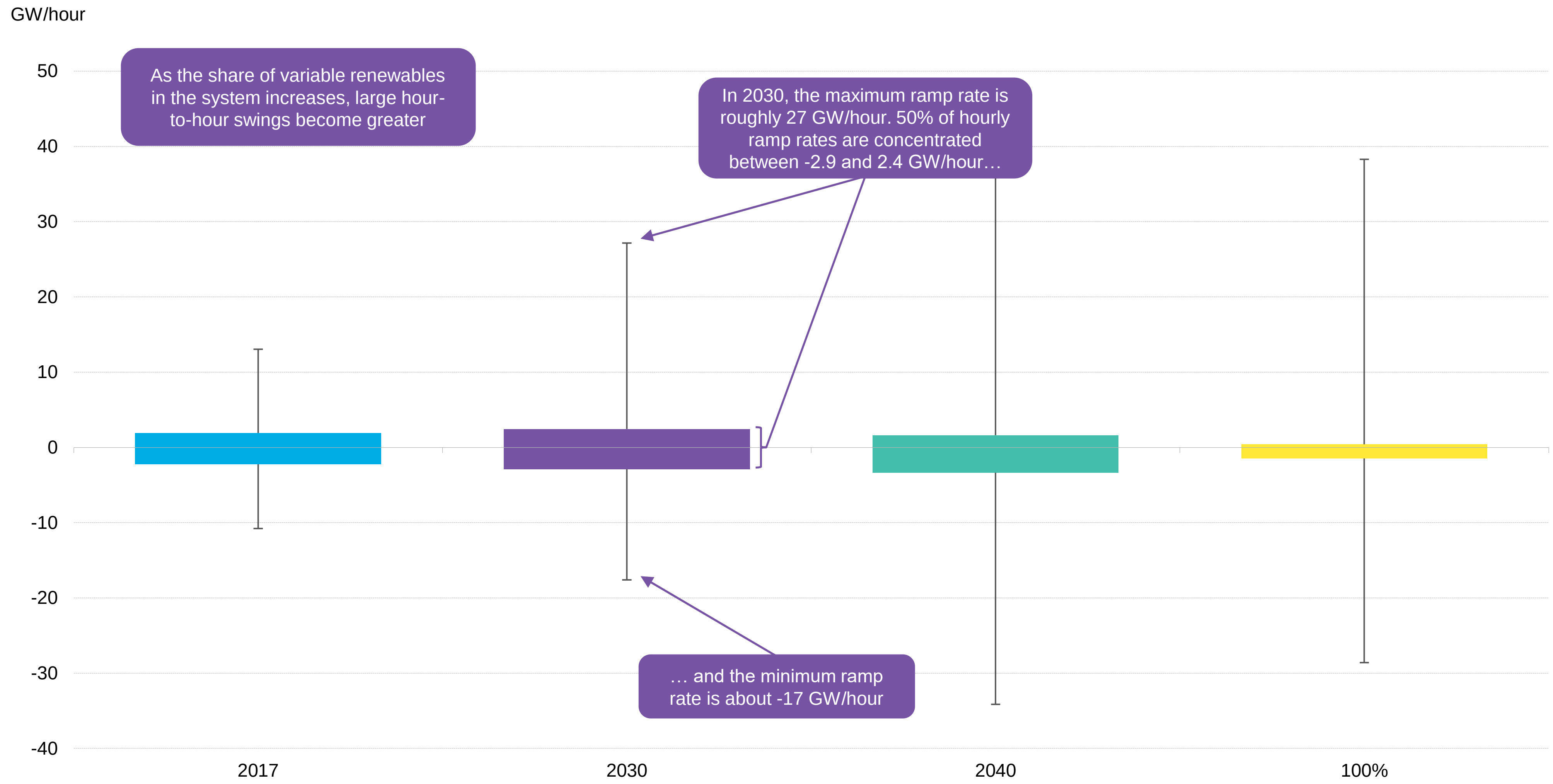
- **In all scenarios, there are some hours when most of demand has to be met by other (non-wind/solar) sources.** As a result, between 84GW and 97GW of back-up are still needed, despite the presence of much higher wind and solar capacity. These can be provided by dispatchable generation, or other sources such as interconnectors, energy storage and demand response.
- **But as wind and solar grow, they meet higher shares of demand**, crowding out other generating sources. Output from non-wind/solar generators is expected to shrink by 29% between 2017 and 2030, and by 44% to 2040.
- **This drives down the utilization rate of 'other' sources used for back-up.** Today, non-wind/solar generators run at around 51% utilization, but that is expected to fall to 40% in 2030, and 27% in 2040.
- These trends point to several possible implications:
  - A growing opportunity for short-run flexibility options, such as energy storage and flexible demand
  - An increasingly difficult operating environment for conventional plants, as they struggle to earn a return from fewer operating hours
  - This could lead to more instances of scarcity, accompanied by very high power prices – or growing out-of-market payments to keep conventional generators online as power market revenues fall

Scenario values

Scenarios	2017	2030	2040	100%
Peak output of other generators (GW)	92	84	97	94
Energy supplied by other generators (TWh)	413	295	231	145
Utilization of other generators (%)	51	40	27	17

Growing system volatility

Distribution of hourly ramp rates across the year



Growing system volatility

Key trends

The chart above shows how often ‘other resources’ (non-wind/solar) in the system have to ramp up and down, to accommodate hourly fluctuations in demand and wind/solar output. This is shown as a box plot illustrating the distribution of all the hourly ramp rates in a year.

- As wind and solar are added to the system, other sources have to ramp up and down more quickly, and more often.
- **Extreme system volatility events increase** as the share of variable renewables increases. This is calculated as the highest hourly upward (**ramp-up**) or downward (**ramp-down**) change in output required from other generators to make up for the shifts in wind and solar output, and in demand.
- **Extreme ramp rates stress the system** as failure to meet them can result in oversupply (requiring energy wastage) or under-supply (threatening system stability). Ramping is also an issue because conventional generators are generally most efficient when run at stable outputs. During changes in output, efficiency drops and costs increase.
- **Increased ramping requirements could be an opportunity for newer technologies** such as battery storage and certain types of flexible demand, which can alter their states of generation/consumption quickly without major cost implications.
- The chart above only addresses hourly changes in demand and in wind/solar output. It does not account for intra-hour fluctuations, for example to manage forecasting errors, or to maintain system frequency.

Scenario notes

2017

- The highest ramp-up is around 13GW in an hour, and the highest ramp-down is around 11GW
- This corresponds to about half of the current German gas fleet turning on or off in one hour

2030

- The highest ramp-up is around 27GW/hour and the highest ramp-down is 17GW/hour
- This corresponds to a third of Germany’s current gas and coal plants turning on or off in one hour

2040

- The highest ramp-up climbs to 38GW in an hour, and the highest ramp-down is around 34GW/hour
- These changes correspond to around 40% of Germany’s dispatchable generation fleet in 2040 turning on or off in one hour

Germany: hourly and daily variability

Analyzing hourly and daily issues

Managing hourly and daily variability

This section explores the short-term dynamics of a high-renewable system in Germany, focusing on issues that arise at the ***hourly*** and ***daily*** horizon. To do so, we have applied five years of historical solar/wind production data to each scenario.

Challenges and opportunities

All four of the issues identified in the previous section are apparent at the daily/hourly level, creating opportunities for technologies that can address them:

- **Reducing volatility:** hour-to-hour variability in demand and wind and solar output creates an opportunity for flexible generation or energy storage / shifting technologies that can smooth this out.
- **Reducing the curtailment of renewables:** excess renewable generation in some hours can be better utilized by shifting it to other hours, or making sure there is enough demand to absorb it.
- **Reducing the need for back-up generation capacity:** technologies with better-suited economics can be deployed and operated during extreme events, reducing the need for more expensive back-up options.
- **Increasing generation asset utilization:** by reducing the back-up capacity requirements, less generating capacity is needed, increasing the utilization of the remaining capacity.

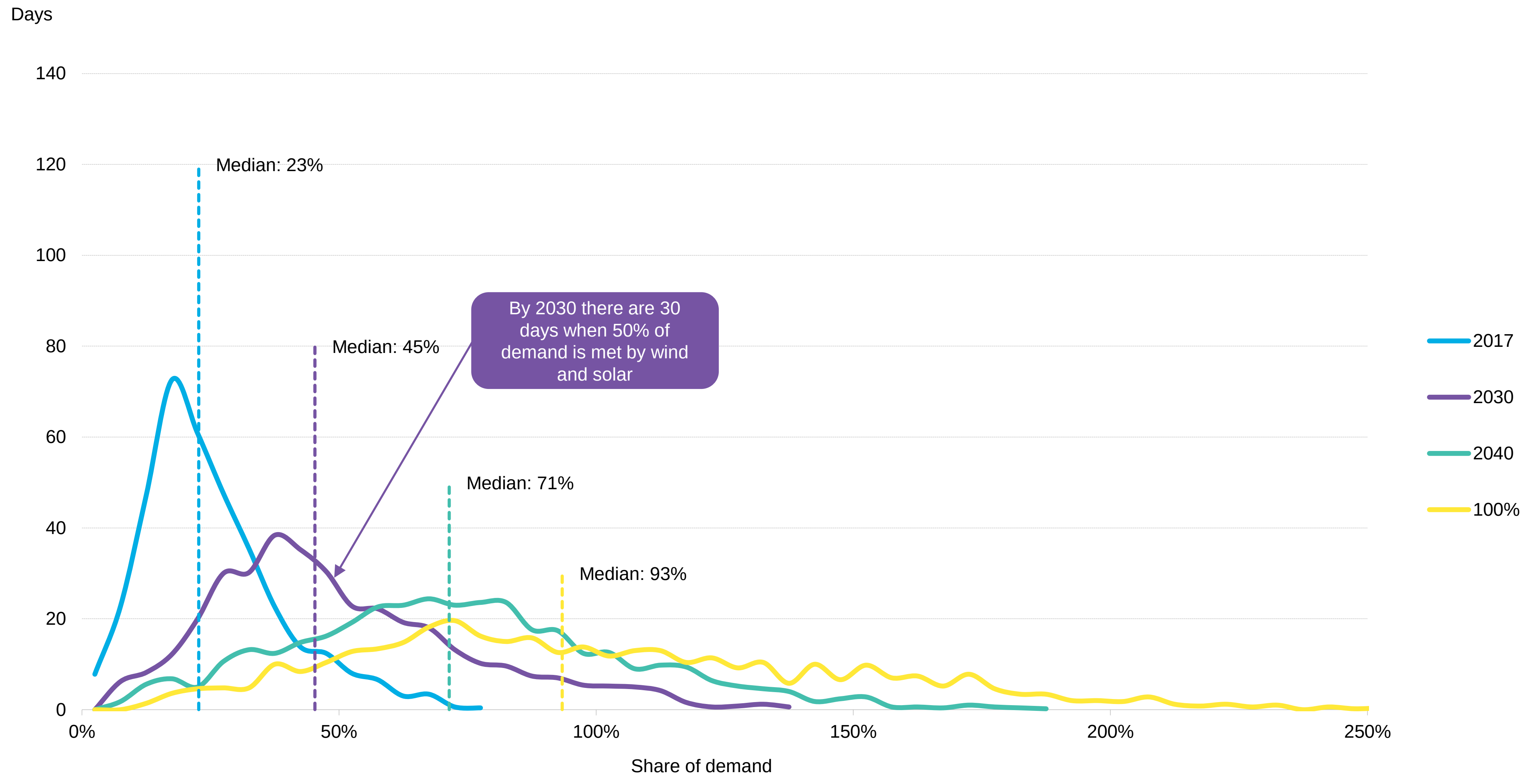
Technology options

To address these issues, system operators can call on a variety of technologies with various advantages and disadvantages, including:

- **Peaking gas plants:** a relatively low capital expenditure approach with high running costs. Peaking plants can help during peak events, and are very agile, but they cannot address curtailment.
- **Demand response:** reduction of power demand through DR technologies is a relatively low-capex approach, but often with a high per-use opportunity cost. Demand response can help reduce peak requirements by reducing load in hours of high system stress.
- **Flexible electric vehicle charging:** by taking control of EV charging, demand can be increased when curtailment happens and decreased during a peak event. This is a low-capex , low-opex option, but requires mass adoption of EVs and smart charging.
- **Batteries:** this is a high-capex, low-opex approach, though their cycle life also imposes an opportunity cost of sorts. Batteries are well placed to address all of the issues above in the short term (hourly/daily). By modifying their charge/discharge rate they can reduce system volatility. They can also reduce curtailment by charging up during high wind and solar output hours. And they can reduce the need for peak by discharging at maximum output during hours of low renewable generation.
- **Interconnection:** Greater interconnection with neighboring countries will allow power to be exported at times of excess, and imported when required to meet gaps in renewables production – assuming that neighbouring countries are not suffering the same issues at the same time.

Variable renewable generation distribution

Number of days for which renewable generation makes up X% of demand



Source: Bloomberg New Energy Finance

Variable renewable generation distribution

Key trends

The chart above shows how often wind and solar account for a certain proportion of daily demand. For example, the blue curve shows that in 2017, wind and solar could account for 20% of demand on roughly 73 days of the year, but they never account for more than 80% of demand in a day.

- As the share of wind and solar in the system increases, there are more days when they meet a higher proportion of demand. This can be seen in the way the curves shift to the right for later years.
  - This also means that there are fewer days when wind and solar are insignificant. For example, by 2030 there are already rather few days when wind and solar produce less than 25% of demand. It will be much more common for wind and solar to produce around 25-60% of demand.
- The curves also become much flatter in later years (especially in the extreme 100% case). This indicates a much greater range of possibilities for how much wind and solar there is relative to demand on a given day:
  - In the 2040 scenario, on a given day wind and solar could produce as much as 190% of demand, or as little as 10%. To put it another way, wind and solar are about as likely to provide 100% of demand as they are to provide 40% of demand.
  - From a system operation perspective, this implies a much broader range of daily scenarios to prepare for.
- The next few pages explore these trends by showing hourly data for typical and extreme (high- and low-renewable) days.

Scenario notes

2017

- On a typical (median) day, wind and solar generate enough to meet 23% of demand.
- Wind and solar occasionally meet more than about 38% of demand in a given day. In very rare occasions they reach 80%.

2030

- On a typical (median) day, wind and solar generate 45% of demand. Even on the lowest day, they meet 10% of demand.
- Wind and solar contribute more than half of demand for 154 days, or 42% of the year. They typically contribute between 33% and 65% (this is the inter-quartile range).
- There are also the first extreme days, when wind and solar generate more than needed – a few with over 50% excess.

2040

- On a typical (median) day, wind and solar generate 71% of demand. Even on the lowest day, they meet 10% of demand.
- Wind and solar meet more than 71% of demand for over half of the year. There are around 72 days when wind and solar over-generate. This over-generation can reach occasional extremes, surpassing 185% of demand.

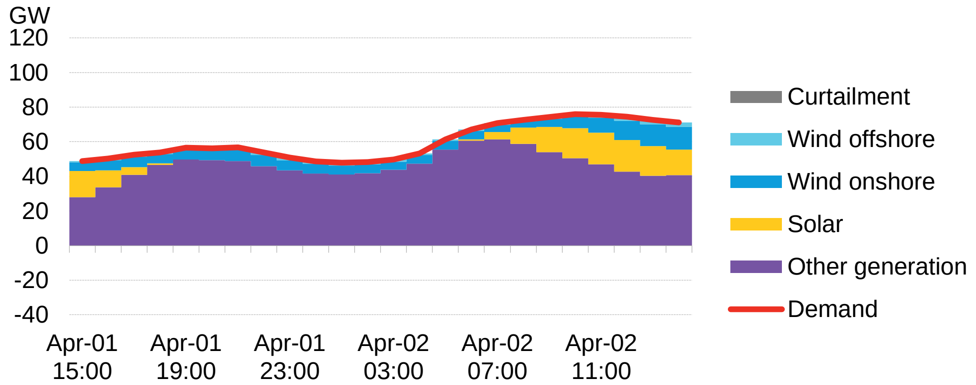
100%

- In the most extreme case, wind and solar can generate more than double daily demand.

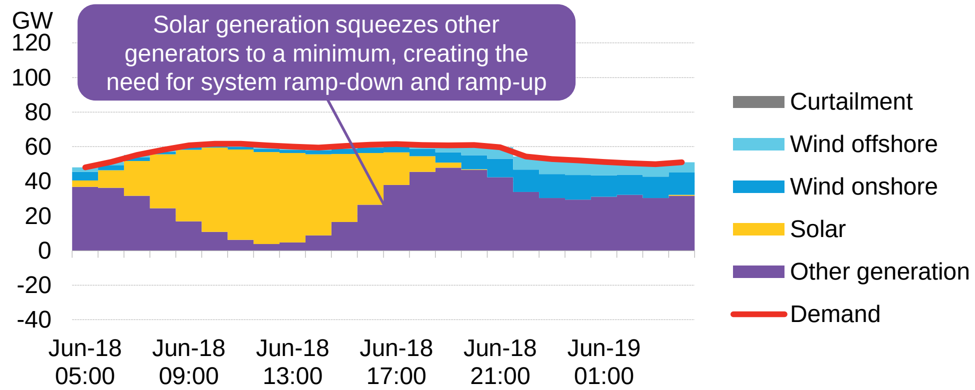
Germany: hourly and daily variability

Median wind and solar 24-hour period

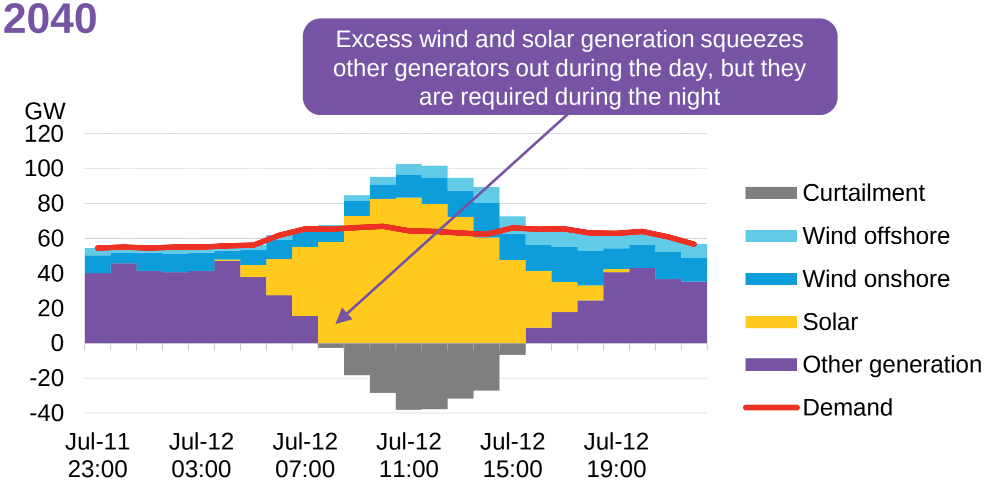
2017



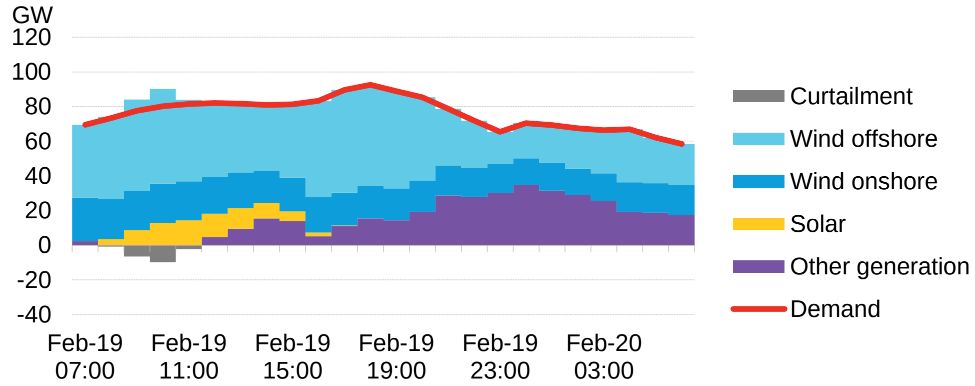
2030



2040



100%



Note: definition of the median renewable 24 hour period: 50% of 24-hour periods in the year have a higher share of renewable generation and 50% of 24-hour periods in the year have a lower share of renewable generation. These are 24-hour periods, not calendar days – so there are 8,736 24-hour periods in a year.

Median wind and solar 24-hour period

Key trends

The charts above show hourly production and demand for the *median day (by wind and solar share)* in each scenario. The purple 'other generation' columns show what other energy sources must provide in order to match hourly demand, after wind and solar production are accounted for.

- Other generation provides less and less energy in future years. This is to be expected for the typical day, as more wind and solar are added.
- Increasing wind and solar introduce more hourly volatility, so other generation must also flex more to accommodate this. This can be seen in the larger up- and down-ramps of the purple columns in later scenarios.
- The maximum other generation needed ranges from 61GW in the 2017 scenario, to 48GW in the 2030 and 2040 scenarios, and 35GW in the 100% case.
- In 2030, high solar generation levels start to result in practically zero need for other generation sources on the median day. This suggests that from 2030 other generators will be faced with full shut-down at some point during many days of the year.
- There is curtailment of wind and solar on a median day in 2040 and the 100% scenario. Curtailment occurs in the middle of the day and is driven by solar generation.

Scenario notes

2017

- None of the described issues are evident on a median day. Other generation adjusts gradually to account for demand changes and modest shifts in wind and solar production.

2030

- Volatility in variable renewable output starts to drive other generators to ramp more dramatically. We also start seeing how other generator output at midday is kept subdued by solar and wind during the night.

2040

- Volatility in renewable energy output becomes more significant. A large slug of solar means that other generators are forced to shut down in the middle of the day. As the sun sets and solar generation decreases, other generators need to ramp up in a matter of hours.

100%

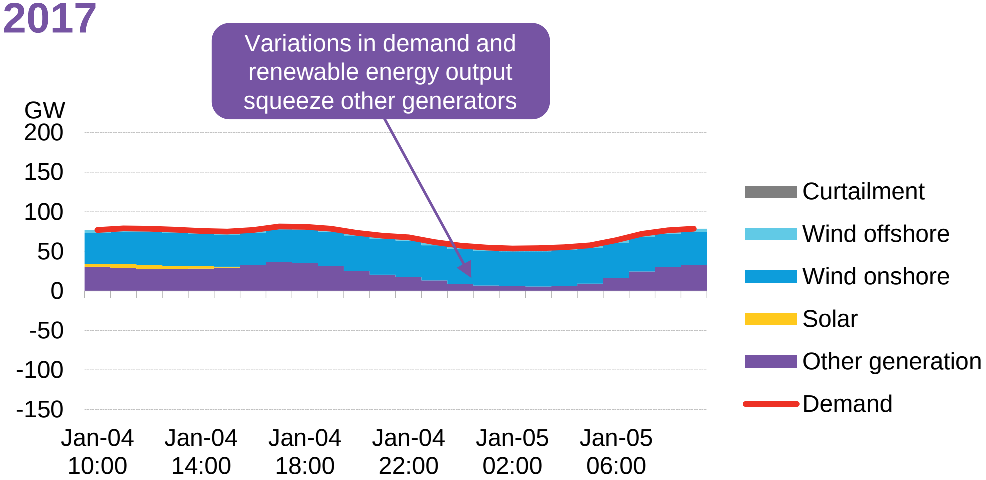
- The median day in the extreme case falls on a winter day in February. The day is dominated by wind generation, a fraction of which is curtailed in the morning. Other generation is called upon to meet evening demand, when solar has stopped producing, and it remains online through the night.

Note: definition of the median renewable 24 hour period: 50% of 24-hour periods in the year have a higher share of renewable generation and 50% of 24-hour periods in the year have a lower share of renewable generation. These are 24-hour periods, not calendar days – so there are 8,736 24-hour periods in a year.

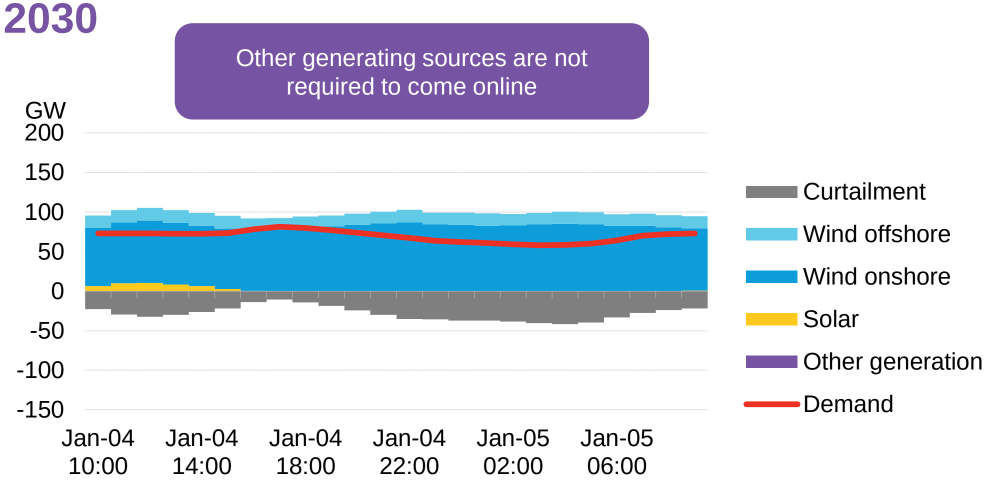
Germany: hourly and daily variability

Highest wind and solar 24-hour period

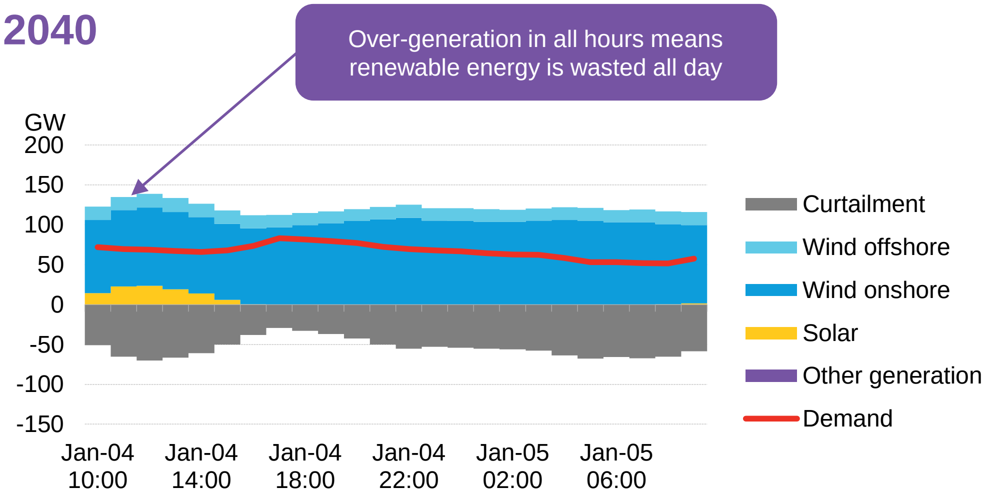
2017



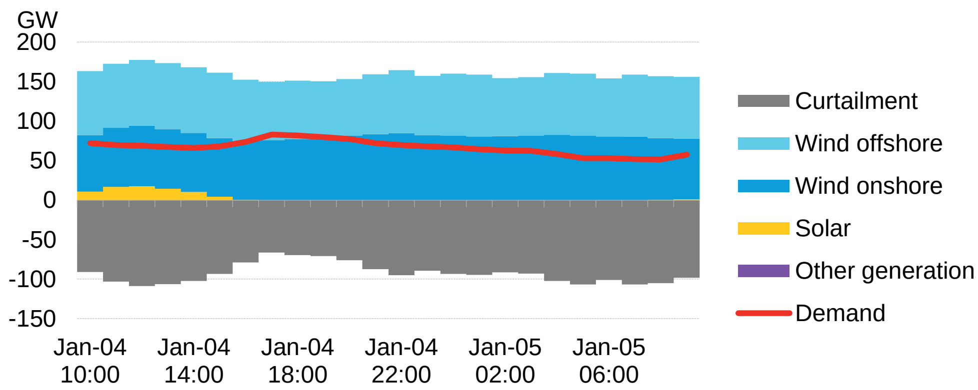
2030



2040



100%



Note: 24-hour periods where wind and solar account for the highest share of demand in the year. These are 24-hour periods, not calendar days – so there are 8,736 24-hour periods in a year.

Highest wind and solar 24-hour period

Key trends

The charts above show hourly production and demand for the *highest day (by wind and solar share)* in each scenario. The purple 'other generation' columns show what other energy sources must provide in order to match hourly demand, after wind and solar production are accounted for. Grey shows curtailment, when wind and solar alone exceed demand.

Looking at the highest wind/solar production day allows us to view the most extreme daily dynamics at work. We can see that:

- On these highest wind/solar days, the role of other energy sources is massively diminished. This happens as soon as 2030, and raises important questions about how conventional and nuclear generators will be able to operate in a high-renewables system. Their ability to flex – or disconnect completely – will become increasingly relevant.
- This also raises questions about how system frequency will be managed, if the power system is dominated by asynchronous generators at certain times.
- Curtailment becomes an issue on these highest days – and could be higher if other generators are not able to switch off, or if grid constraints become a bottleneck. However, we note that overall annual curtailment remains around 5% of wind/solar production in 2030, and 14% in 2040 – the days shown here are the extreme case.

Scenario notes

2017

- The highest wind and solar 24-hour periods start to squeeze other generators, but they still play an important role in meeting peak demand.

2030

- There are days when wind and solar generate enough to meet all of demand.
- On these extreme days, every hour there is excess energy that will need to be curtailed or absorbed.

2040

- Days when wind and solar energy is enough to meet all of demand are more common.
- The amount of excess energy that would have to be curtailed or stored amounts to 45% of wind and solar generation and is equivalent to 82% of the day's demand.

100%

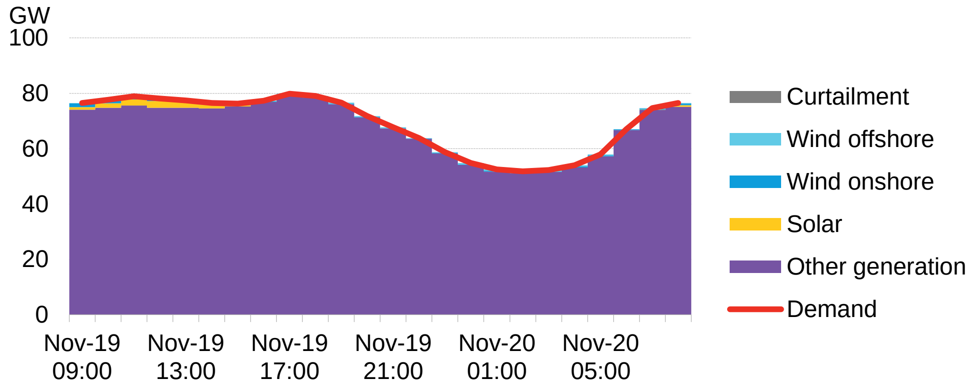
- This is the most extreme day of the most extreme case. Wind and solar produce far more energy than the system needs.

Note: 24-hour periods where wind and solar account for the highest share of demand in the year. These are 24-hour periods, not calendar days – so there are 8,736 24-hour periods in a year.

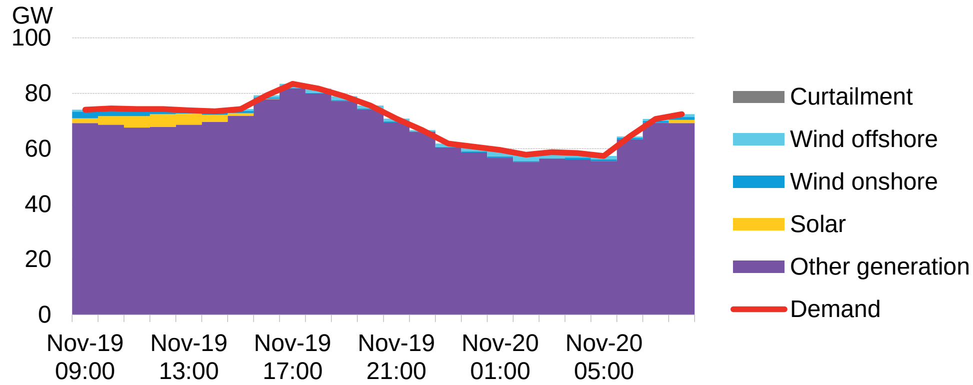
Germany: hourly and daily variability

Lowest wind and solar 24-hour period

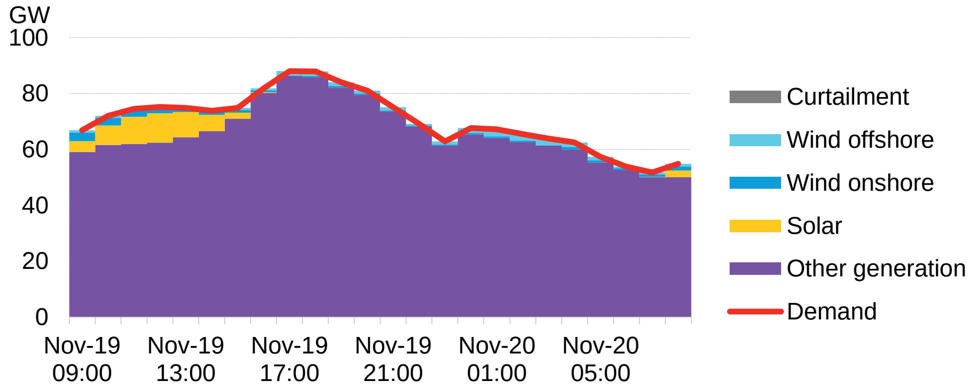
2017



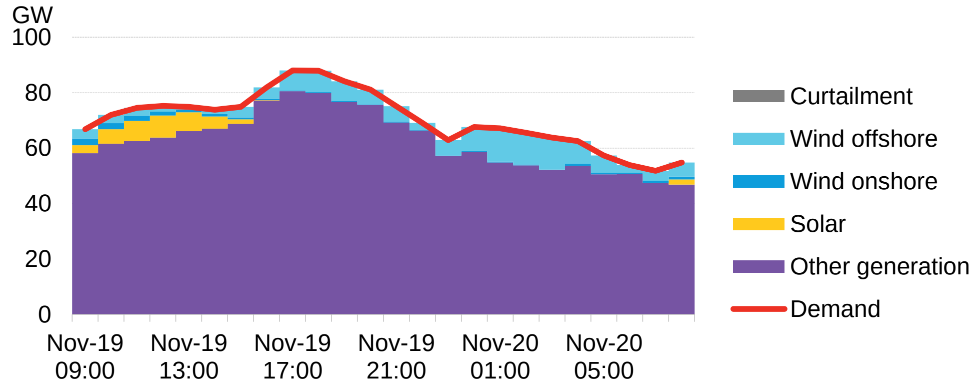
2030



2040



100%



Note: 24-hour periods where wind and solar account for the lowest share of demand in the year. These are 24-hour periods, not calendar days – so there are 8,736 24-hour periods in a year.

Lowest wind and solar 24-hour period

Key trends

The charts above show hourly production and demand for the *lowest day (by wind and solar share)* in each scenario. The purple 'other generation' columns show what other energy sources must provide in order to match hourly demand, after wind and solar production are accounted for.

- Even with the addition of large amounts of wind and solar capacity, there will be days when renewables output will be close to zero. In Germany in 2040, this extreme occurs on a winter's day when there is cloud cover but little wind.
- Over such days, other generating sources will have to contribute almost all energy and power requirements.

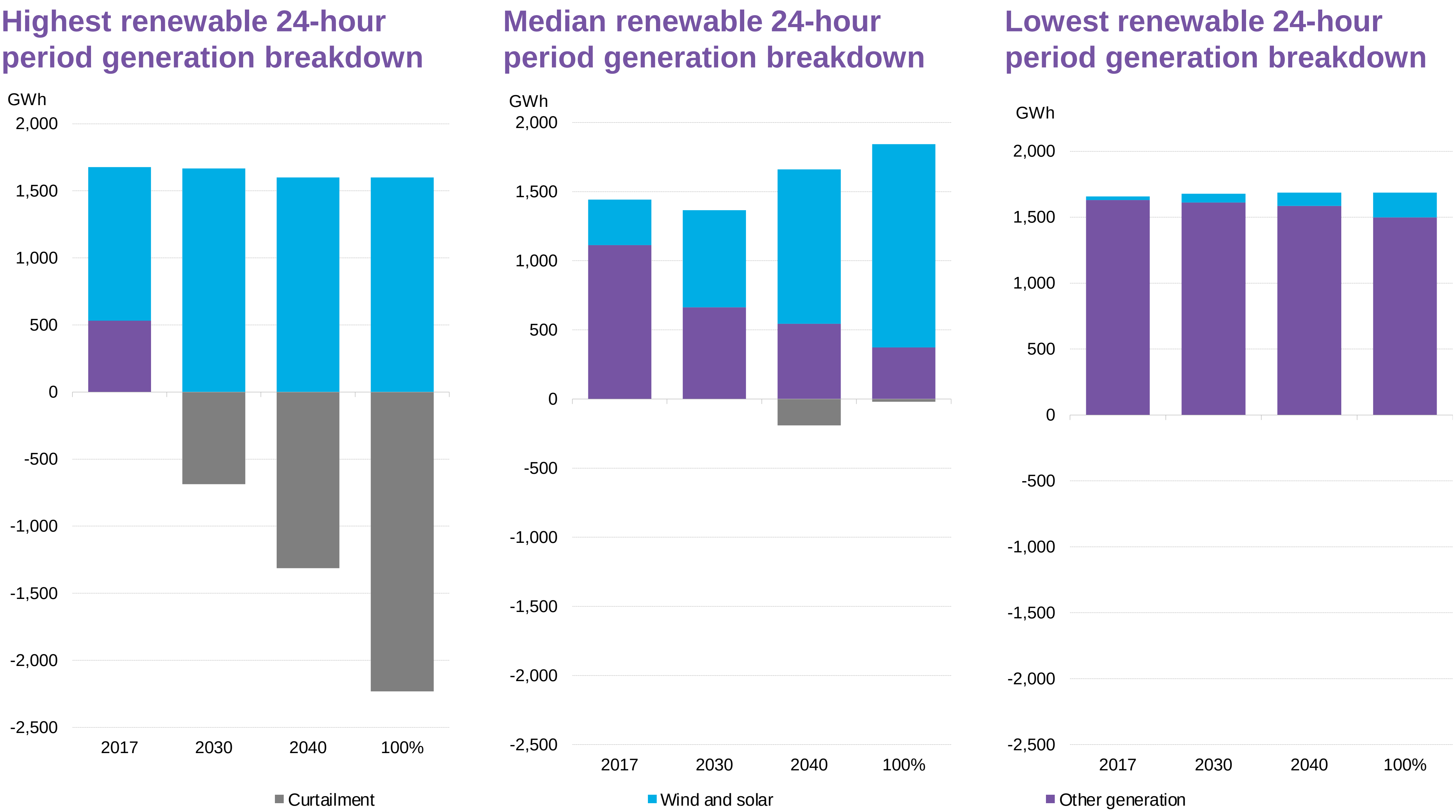
Scenario notes

- In the 2030, 2040 and 100% scenarios, there is still some wind and solar production, even on the most extreme low day. However, the overall picture remains the same as in 2017 – the vast majority of demand must be met by other sources.

Note: 24-hour periods where wind and solar account for the lowest share of demand in the year. These are 24-hour periods, not calendar days – so there are 8,736 24-hour periods in a year.

Germany: hourly and daily variability

Summary of challenges and opportunities



Summary of challenges and opportunities

Challenges

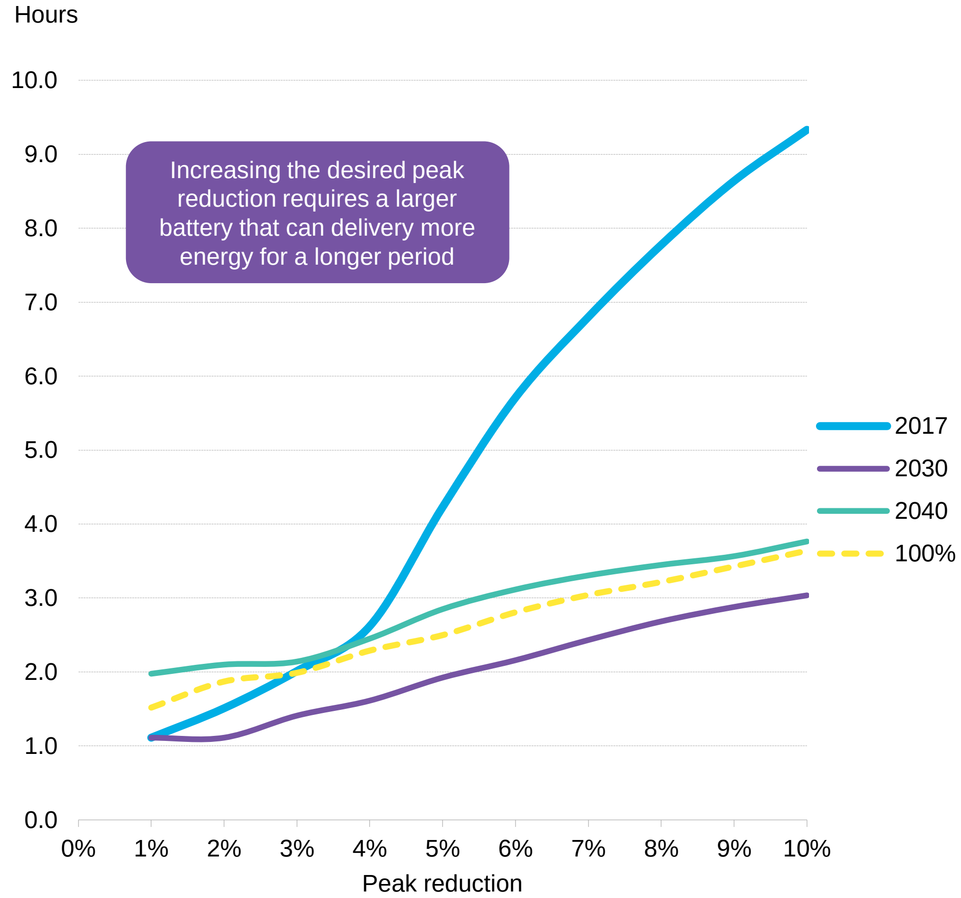
- **Volatility**
  – The demands placed on other sources of energy can be very volatile hour-to-hour, especially on non-extreme days (where wind and solar generate some, but not the vast majority, of demand).
- **Curtailment**
  – The highest renewable energy output days lead to significant curtailment in all scenarios, with the exception of 2017.
- **Back-up is required in all scenarios**
  – In all scenarios, the lowest variable renewable energy days require other sources to step in and meet almost 100% of energy and capacity requirements.
  – Over median/typical days, other generating sources will be needed by the system to plug short-term gaps that variable wind and solar cannot meet.
  – Only on the highest wind and solar days, is there no need for other generation.
- **Low generation asset utilization**
  – Power generators that provide back-up need to be sized such that they can meet peak demand, but they will operate at lower utilization rates as wind and solar grow. This is likely to drive up unit costs of generation for these plants.

Opportunities for new technologies

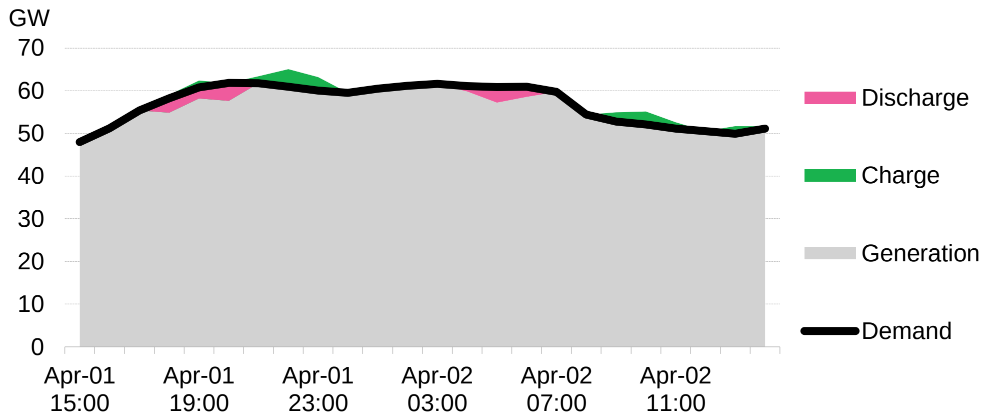
- **Absorbing volatility**
  – Batteries and some sources of flexible demand can quickly adjust their charging/discharging patterns to smooth out volatility.
- **Reducing the curtailment of renewables**
  – As a form of flexible demand, electric vehicles can shift their charging within the day to coincide with high renewable generation periods, reducing the extent of curtailment.
  – Batteries can be used to store some of the excess energy and deploy it at later hours, reducing the need for other generators to come online.
- **Reducing the need for back-up generation**
  – Demand response technologies can help reduce consumption when the system is stressed. Electric vehicles can also avoid charging at these times.
  – Batteries can charge up as a peak event is approaching and discharge during the peak event.
- **Increasing generation asset utilization**
  – If these technologies are appropriately deployed and optimized, this can help to reduce system peak requirements. This in turn would mean that less back-up generation is required, increasing the utilization of the remaining capacity.

Case study: batteries to manage hourly peaks

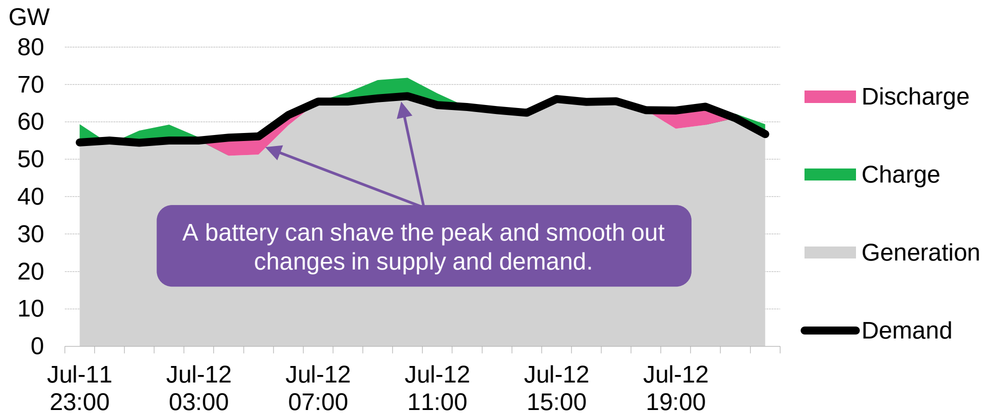
Peak shaving (size of battery based on desired peak reduction)



5% peak reduction with battery, 2030



5% peak reduction with battery, 2040



Case study: batteries to manage hourly peaks

Peak shaving case study

- **Batteries can help shave peaks**. They can charge when the system is not under stress, during hours of low to moderate output from other generators, and discharge when demand peaks. This reduces the maximum capacity of other generators needed in the system.
- **Longer peaks means bigger batteries.** To reduce peaks further does not just require more batteries, but also bigger batteries. Not only is more battery capacity required (MW) but, as remaining peak durations inevitably get longer, these batteries are also required to hold more energy (MWh).
  - For example, to reduce peak capacity in 2040 by 4% takes a 2.5-hour battery, whereas to reduce peak by 8% takes a roughly 3.4-hour battery.

Other use cases for batteries

- Batteries are also suited to addressing other short-term issues that arise from increasing penetration of wind and solar.
  - **Low utilization of other generation:** by reducing the peak generation capacity requirements, the average utilization of the remaining generators will increase.
  - **Variability**: batteries can quickly swing from charging to discharging, offsetting changes in variable renewable output, demand, or both.
  - **Curtailment of renewables**: batteries can store the energy not needed by consumers in hours of high wind and solar output. When non-renewable energy is needed again, batteries can discharge the energy they stored.

Germany: weekly, monthly and seasonal variability

Analyzing weekly to seasonal issues

Managing longer-term variability

This section explores the longer-term dynamics of a high-renewables system in Germany, focusing on issues that arise at the ***weekly to seasonal*** horizon.

Challenges

- The main challenge explored in this section is that of long-term resource adequacy. That is, ensuring that demand can be met during longer periods of weeks and months when renewables production may be low due to weather conditions. While these periods are not guaranteed to happen every month or every year, they will certainly occur from time to time and it will be necessary for the power system to be prepared for them.
- For this section, we have again applied five years of past solar/wind production data to each scenario, in order to find the most extreme weeks and months.
- Curtailment is also of interest at the longer-term horizon. There will be long periods of significant wind and solar excess. These may indicate opportunities for long-term storage: if excess energy can be stored for long periods of time and then released, it can help address the resource adequacy problem outlined above.

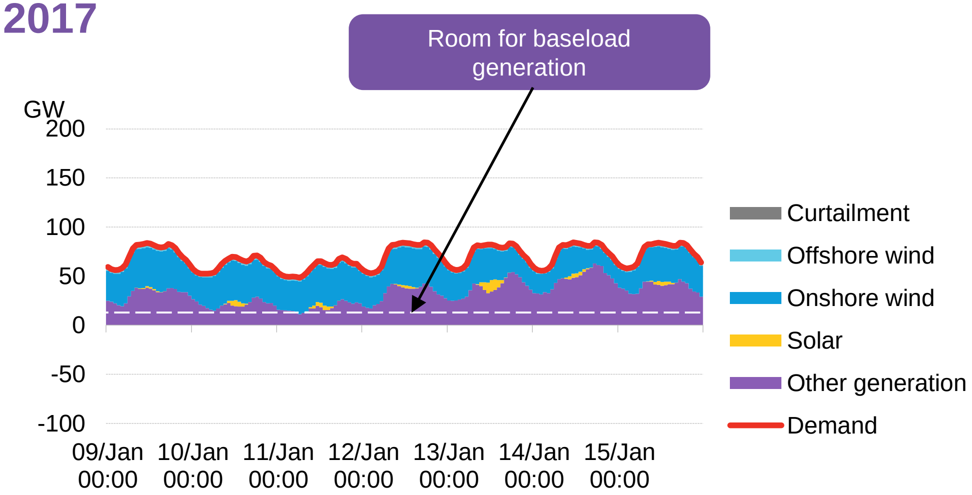
Opportunities

- There is a potential opportunity for future technologies to shift energy over longer periods of time – weeks, months and seasons. This is a significant technical challenge, but could:
  - Reduce the need for back-up capacity. We find that by 2030, the required generating capacity could be reduced by 26% if energy can be shifted across a month instead of just a day. By 2040, generating capacity can be reduced by 13% if energy can be shifted across a quarter instead of a month.
  - Increase the utilization of the remaining back-up assets, as a result of the reduced back-up capacity requirement.
  - Reduce curtailment: by 2040 there will be multiple weeks with more renewable generation than consumption; this will require storing or shifting demand for at least multiple days
- Batteries and flexible demand technologies are not currently able to shift energy across weeks or months, due to their economics and characteristics. Demand cannot be deferred for weeks, and the sheer scale (and cost) of batteries needed for seasonal storage would be prohibitive.
- Currently, no seasonal storage technologies are economic; however, in future, technologies such as power-to-gas and hydrogen storage may become more cost-effective. Until they are, a full complement of generating capacity is required.
- Still, we find that at about 60% wind and solar penetration (2040), there is not a strong case for seasonal storage, as the benefits to the system of being able to shift energy over longer periods diminish sharply with the length of the period.

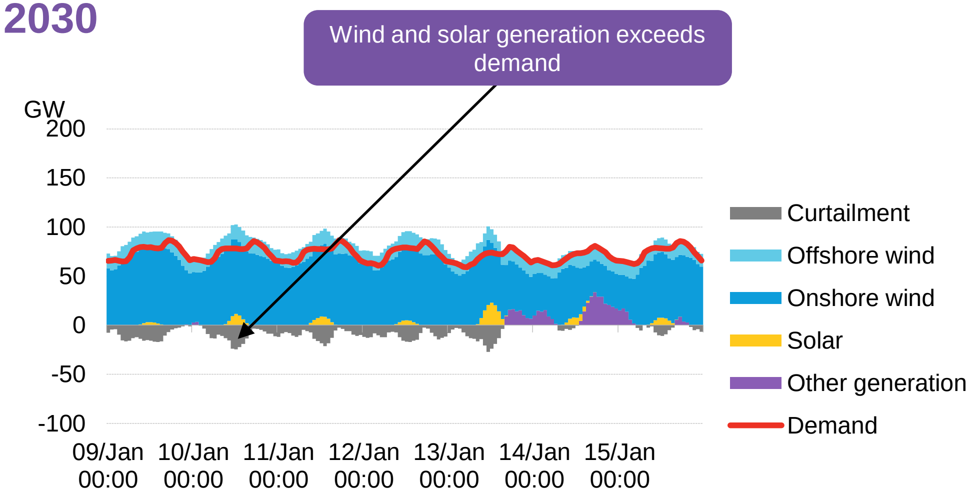
Germany: weekly, monthly and seasonal variability

Highest wind and solar output week

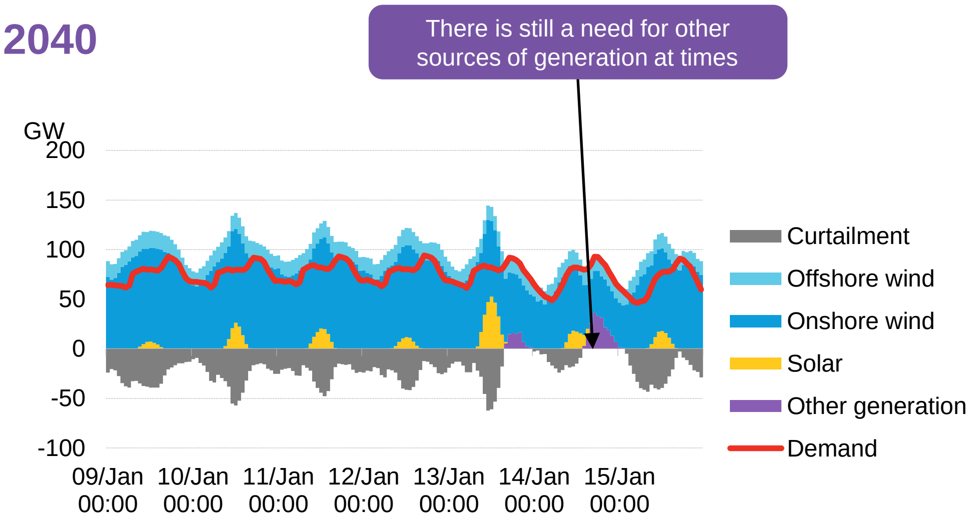
2017



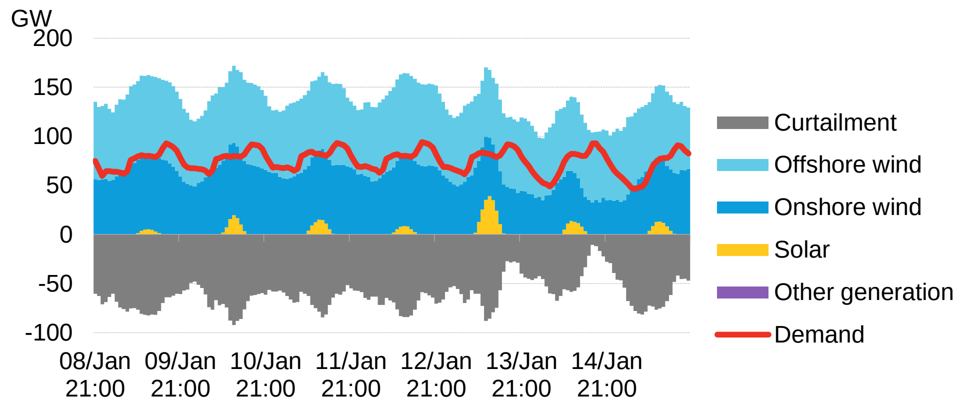
2030



2040



100%



Note: a week is defined as a 168 hour period, not a calendar week.

Highest wind and solar output week

Key trends

The charts above show hourly production and demand for the *highest week (by wind and solar share)* in each scenario. The purple 'other generation' columns show what other energy sources must provide in order to match hourly demand, after wind and solar production are accounted for. Grey shows curtailment, when wind and solar alone exceed demand.

- In all scenarios, the highest week is the same: it occurs in January during a period of high winds.
- In general, the role of other generation diminishes in the later years. However, in 2030 there is still reliance on other generation at one point in this highest week of wind and solar production. This is different from the highest individual day (see previous section), where other generation wasn't needed.
- By 2040, wind and solar production is so great that there is almost constant curtailment, though, as in the 2030 scenario, back-up is required at some point in the week.

Scenario notes

2017

- Only in 2017 is there a requirement for about 11GW of baseload generation, running flat out at steady output. Even during the periods of highest wind and solar output, there is a minimum level of other generation required.

2030

- By 2030, there are weeks where wind and solar generation exceeds demand at some point every day and accounts for more than the total demand over the period. This leaves no room for technologies that need to run flat-out, such as nuclear power**.**

2040

- However, even in 2040 other sources of generation are still required at times during the highest wind and solar output weeks (though they play a relatively small role supplying a mere 2% of energy). Renewable excess is very significant in this week, with 23% of wind and solar output curtailed.

100%

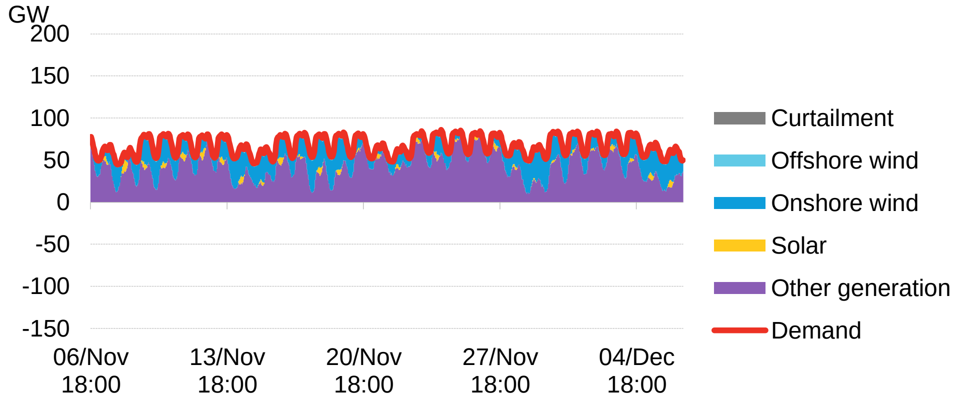
- Other resources are not needed in the 100% scenario, where 45% of renewable energy is curtailed in the absence of storage.

Note: a week is defined as a 168 hour period, not a calendar week.

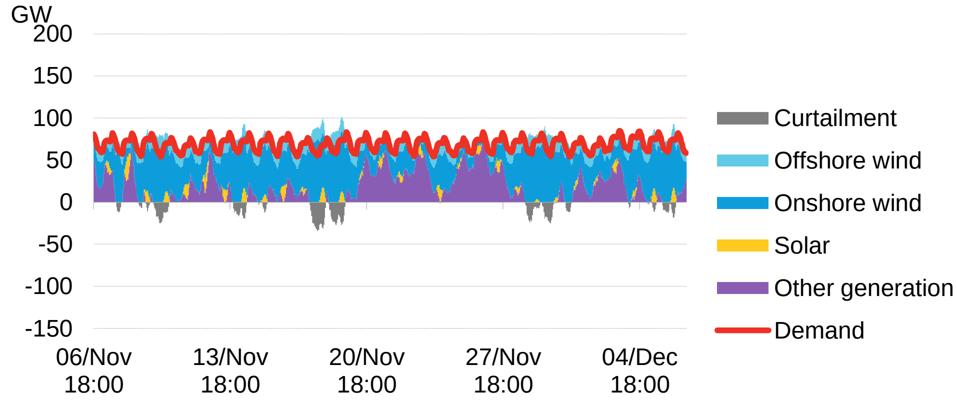
Germany: weekly, monthly and seasonal variability

Highest wind and solar output month

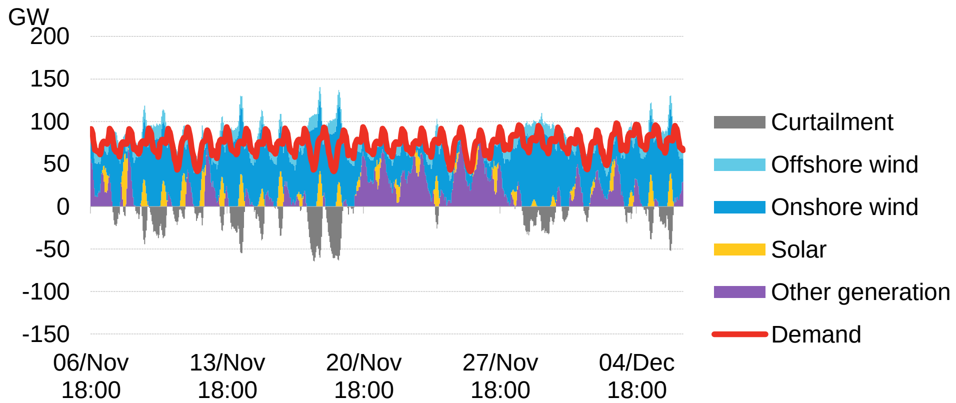
2017



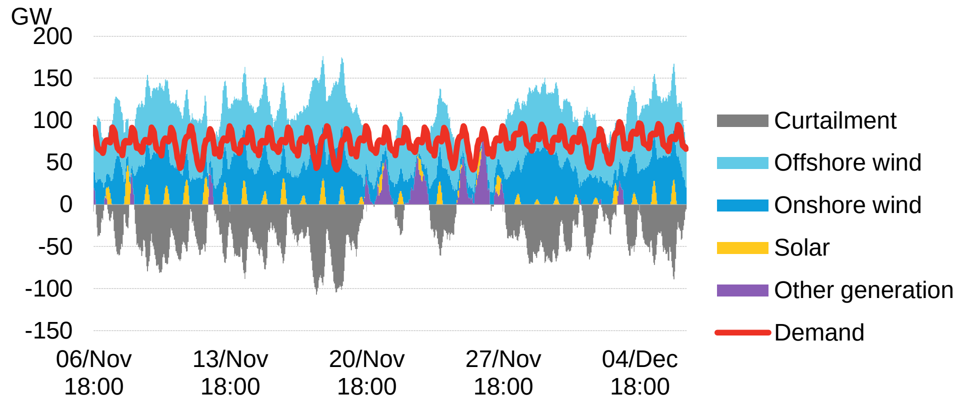
2030



2040



100%



Note: a month is defined as a 730 hour period, not a calendar month.

Highest wind and solar output month

Key trends

The charts above show hourly production and demand for the *highest month (by wind and solar share)* in each scenario. The purple 'other generation' columns show what other energy sources must provide in order to match hourly demand, after wind and solar production are accounted for. Grey shows curtailment, when wind and solar alone exceed demand.

- We see similar trends for high wind/solar output months as we do at the one-week level.
- In these high-production months in 2030 and 2040, wind and solar energy frequently meet most or all of demand. Other generation plays a diminished role, but is still very much needed in all scenarios.
- While there is currently a need for baseload generation, by 2030 there are entire months with no room for generators that are always on.
- By 2040, wind and solar generation surpasses demand more and more frequently, doing so for several significant periods in this high month. In the absence of energy storage or demand shifting, this excess energy is curtailed.

Note: a month is defined as a 730 hour period, not a calendar month.

Scenario notes

2017

- As in the ‘weeks’ analysis, only in 2017 is there a requirement for baseload generation, running flat out at steady output. The need is for about 10GW of this.

2030

- In 2030, wind and solar do not exceed demand every day for a month (unlike in the ‘weeks’ analysis). However, there is clearly little room for baseload generators in this month. There are a few days here and there where some generators could run non-stop, but these periods are relatively short and the energy provision needed (27%) is much lower than in 2017 (63%).

2040

- Other sources of generation are required at times during the highest wind and solar output months, supplying a fifth of generation. They still play an important role, but opportunities to run uninterrupted for multiple days are very rare.
- There is significant curtailment in the month (13%), but not for the whole month – it is concentrated within a two-week period.

100%

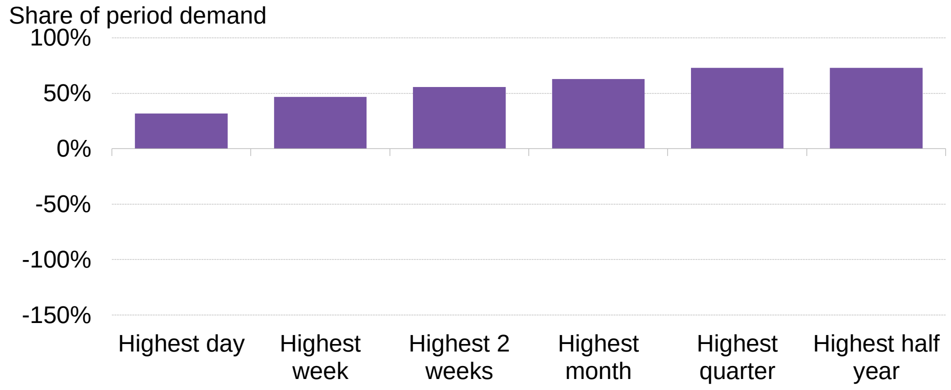
- Other resources are needed for a few hours even in the 100% scenario, though only for short periods. There is a large amount of excess renewable energy across the month, equivalent to about 34% of wind and solar generation.

Germany: weekly, monthly and seasonal variability

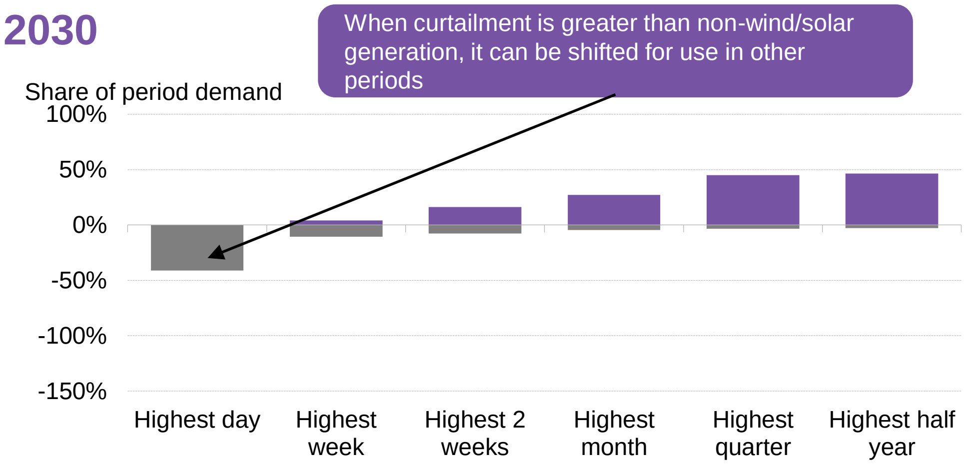
Opportunities to shift excess energy during the highest wind and solar output periods

Share of demand met by other resources, and share of curtailment, in highest-wind/solar periods (days, weeks, etc.)

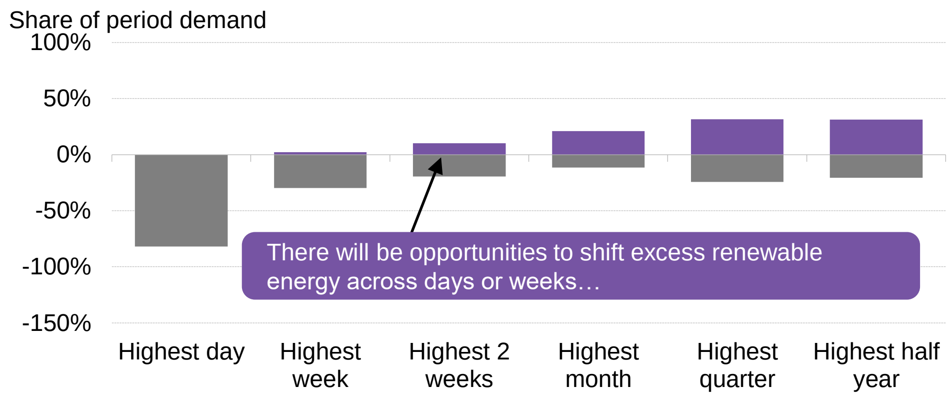
2017



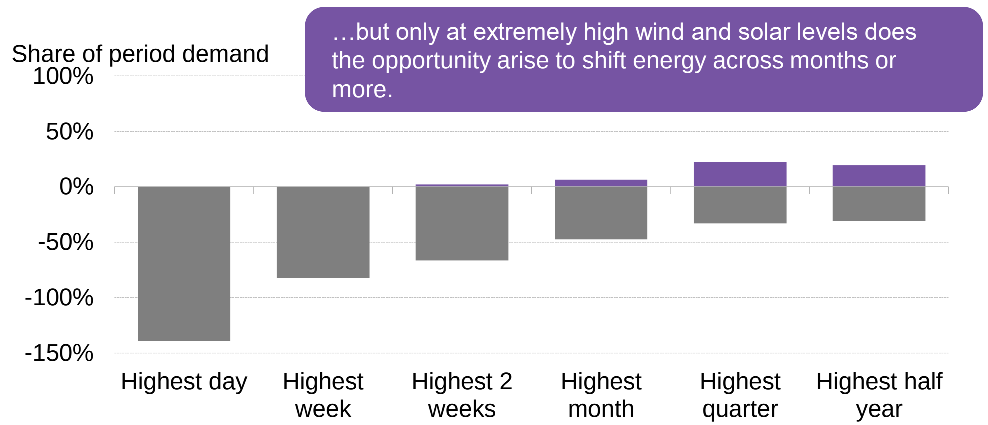
2030



2040



100%



■ Non wind and solar generation ■ Curtailment

Opportunities to shift excess energy during the highest wind and solar output periods

Key trends

The charts above show, only for the *highest* wind/solar output periods (days, weeks, months etc) in each scenario, how much of demand is met by other generation and how much renewable energy is curtailed.

- Clearly, as more wind and solar are added, these periods see less and less demand being met by other resources, and more curtailment. This is evidenced by all the columns moving lower (and grey negative areas appearing) as we progress through the scenarios.
- Where we see columns that show both purple and grey, this indicates that there is both excess renewable energy and a need for back-up within the same high-output period. This implies an opportunity to store excess renewable energy and release within that same period.
- This starts to occur in 2030 at the day level – ie, there is opportunity to shift energy within days in that year.
- In 2040, we see this opportunity at the week, 2-week and even month level. However, curtailment at the quarter- and half-level (ie, seasonal level) is not large enough relative to the need for back-up, to be worthwhile storing and shifting.
- Only in the extreme, 100% scenario can energy shifting at the multi-month level start to make sense.

Scenario notes

2017

- There is no curtailment even in these highest periods, so there is no opportunity shift excess energy.

2030

- On the highest wind/solar week, only about 4% of demand is met by other sources, and 11% of renewable energy is curtailed. This indicates an opportunity to store and shift that surplus energy to meet the demand (removing the need for back-up on that week and reducing it in other periods).

2040

- The highest-wind/solar day, week and 2-week period each see curtailment (19-82%) that is greater than the net demand that needs to be met by back-up resource (0-10%). This indicates an opportunity to store and shift energy within these periods, as well as to other periods.
- However, there is reduced opportunity to shift energy across longer periods, as even in the highest months excess energy is not enough to replace back-up generation.

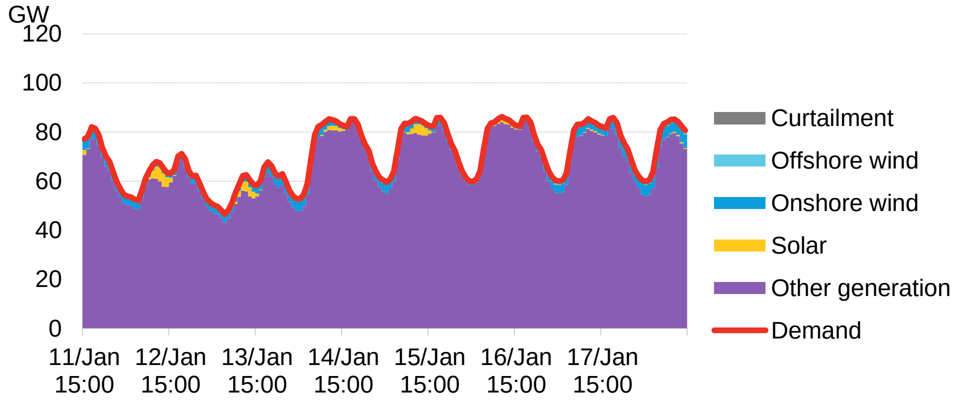
100%

- In this extreme case, there is an opportunity to do large-scale seasonal storage, shifting energy across months and even across seasons.

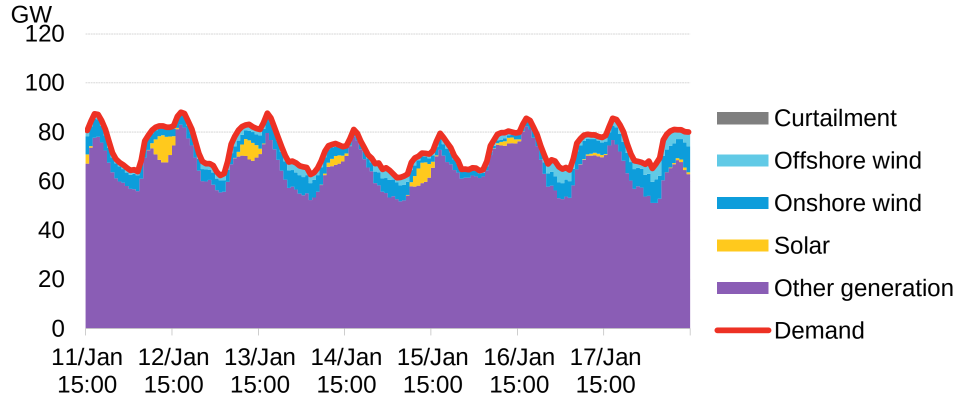
Germany: weekly, monthly and seasonal variability

Lowest wind and solar output week

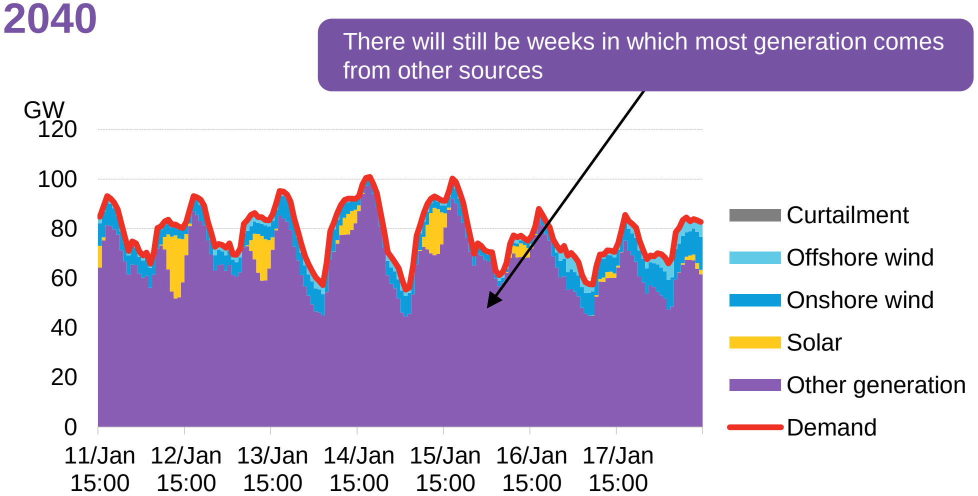
2017



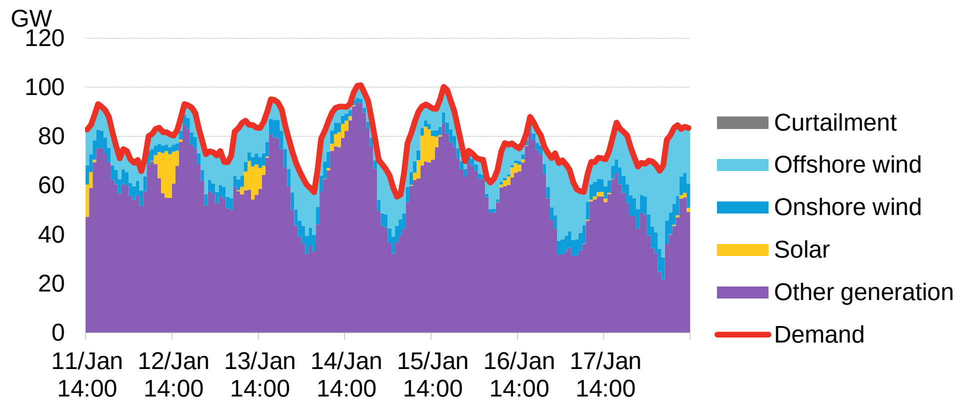
2030



2040



100%



Note: a week is defined as a 168 hour period, not a calendar week.

Lowest wind and solar output week

Key trends

The charts above show hourly production and demand for the *lowest week (by wind and solar share)* in each scenario. The purple 'other generation' columns show what other energy sources must provide in order to match hourly demand, after wind and solar production are accounted for. Grey shows curtailment, when wind and solar alone exceed demand.

- Across all scenarios, there are weeks when most generation has to come from other sources. These weeks see little variable renewable energy generation and require substantial output by back-up capacity.
- In Germany, where solar generation plays an important role, the weeks with the minimum amount of wind and solar generation happen during a wind still period in winter when the sun does not shine much.
- Low wind and solar weeks require about 80% of generation to come from other sources, even by 2040. Unlike the highest weeks and months of wind and solar generation, these low weeks do have room for baseload resources to run throughout the period.

Scenario notes

2017

- 94% of demand is met by non-wind/solar generators in this low week.

2030

- Despite the growth in wind and solar capacity, the lowest week in 2030 still sees 88% of demand met by other generators.
- On average, 65GW of other generation is online during this period.

2040

- Even in 2040, the lowest week still sees 85% of demand met by non-wind and solar generation.
- On average, 67GW of other generation is online during this week.
- The figures for 2040 are higher than in 2030 due to a change in the wind and solar mix (slightly less wind and more solar) and the added demand from electric vehicles.

100%

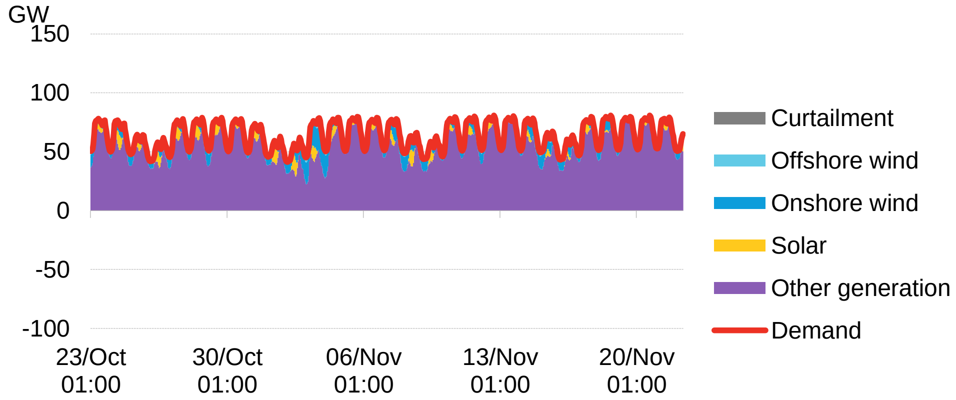
- Even in this scenario, where there is enough wind and solar to supply annual power demand, there are weeks when other sources must meet as much as 75% of demand.

Note: a week is defined as a 168 hour period, not a calendar week.

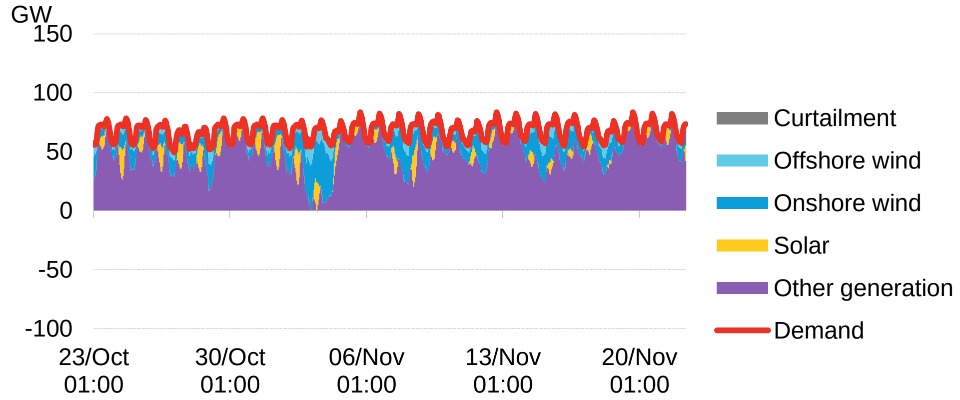
Germany: weekly, monthly and seasonal variability

Lowest wind and solar output month

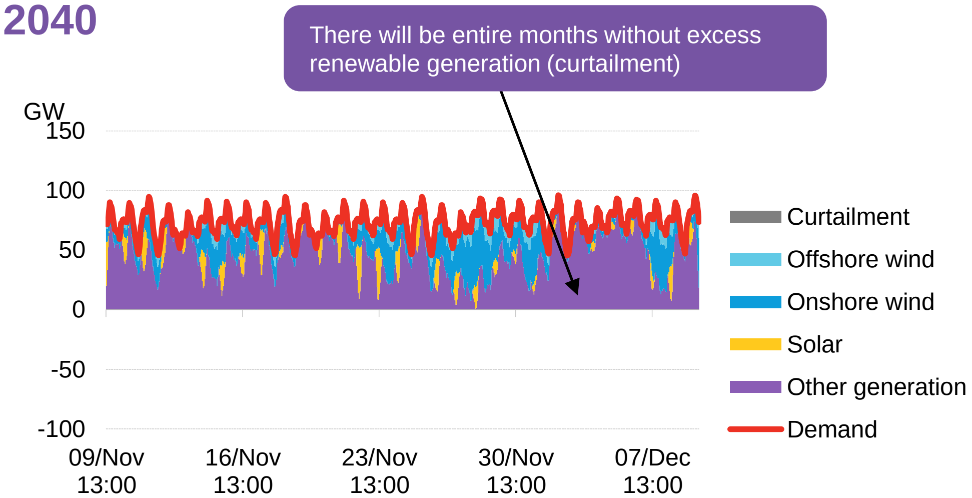
2017



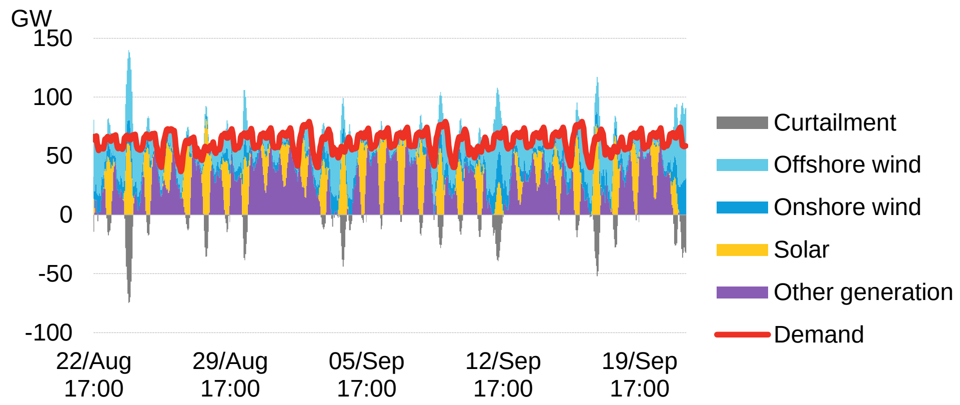
2030



2040



100%



Note: a month is defined as a 730 hour period, not a calendar month.

Lowest wind and solar output month

Key trends

The charts above show hourly production and demand for the *lowest month (by wind and solar share)* in each scenario. The purple 'other generation' columns show what other energy sources must provide in order to match hourly demand, after wind and solar production are accounted for. Grey shows curtailment, when wind and solar alone exceed demand.

- Low wind and solar output periods can last for whole months, not just weeks at a time. Here we see month-long periods in autumn where wind and solar production remain low.
- The amount of generation required from other sources declines from 86% to about 70% from 2017 to 2030. Around 63% of generation has to come from other sources in 2040 during low wind and solar output months.

Note: a month is defined as a 730 hour period, not a calendar month.

Scenario notes

2017

- 86% of demand is met by non-wind/solar generators across this month-long period of low renewable generation.

2030

- By 2030, low-renewables months need less support from other generators: they supply 70% of demand.
- On average, 48GW of other generation is online during this period, but it needs to be flexible to account for changes in renewable production and demand.

2040

- In the low-wind/solar month in 2040, other sources still need to supply around 63% of demand. Though there are no moments of excess wind and solar generation, nearly all other sources of generation will have to switch off at some point even during the lowest wind/solar month of 2040.
- On average, 46GW of other generation is online during this week, and as in 2030 it needs to be flexible.

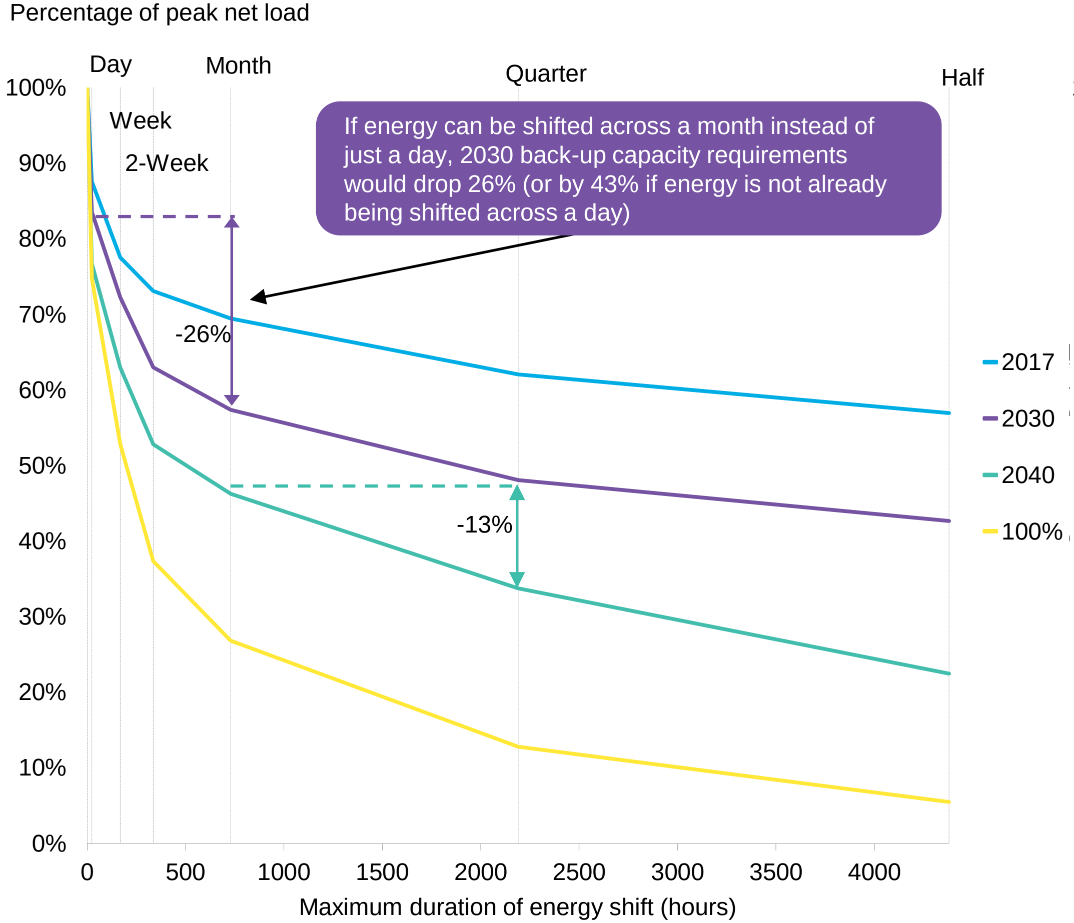
100%

- In this scenario, even low-renewable months see instances of excess renewable energy output. Demand for other sources of generation becomes highly volatile on a daily basis due to increased solar generation. Daily storage could help mitigate these swings.

Germany: weekly, monthly and seasonal variability

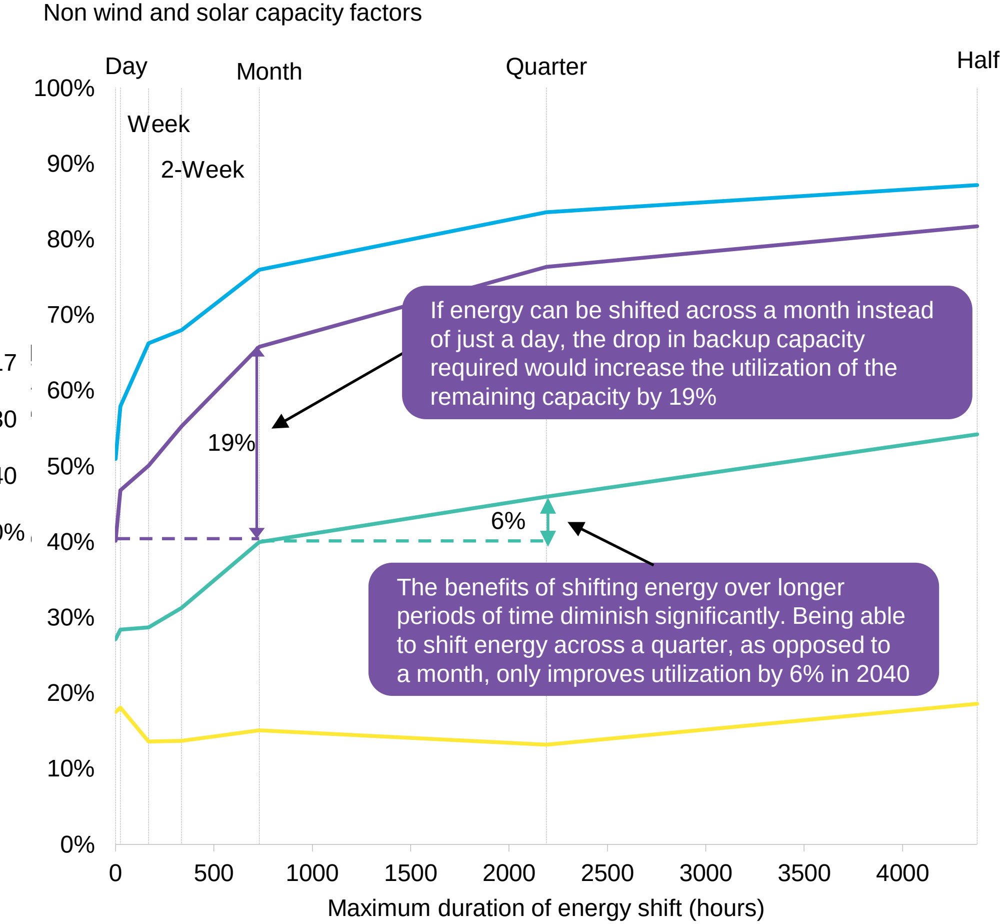
Opportunities for long-term energy shifting

Opportunity to reduce back-up generating capacity



Source: Bloomberg New Energy Finance

Opportunity to increase non wind and solar capacity utilisation



Source: Bloomberg New Energy Finance

Opportunities for long-term energy shifting

Energy shifting to reduce back-up requirement

- As illustrated in previous slides, back-up is needed to meet both short-term peaks (hours, days) and longer periods of low renewables production (weeks, months).
- The left-hand chart above explores what duration of energy shifting / storage would be required to take away the need for back-up generation. The highest peaks – i.e. hours when almost all peak load has to be met with back-up capacity – can be reduced using short-duration storage. As the length of the period over which energy is shifted increases, so does the amount of energy that needs to be stored.
- However, these short, high peaks only account for a small amount of back-up capacity. To reduce back-up capacity considerably, longer storage / shifting is needed. For example, in 2017, an energy shift of a couple of hours is enough to reduce needed back-up capacity by 12%, but to reduce it by 22% requires the ability to shift energy for up to a day.

Increasing back-up utilization

- The right-hand chart above illustrates the impact that longer storage durations could have on back-up utilization. As discussed previously, higher penetration rates of wind and solar lead to lower utilization of back-up generation. (This can be seen in the chart: the lines are lower for higher wind/solar scenarios). This has the effect of hurting the economics of conventional generators, reducing their operating hours and increasing their costs.
- If energy shifting / storage can reduce back-up capacity requirements, this will have the effect of improving utilization – and economics – of the remaining back-up generators.
- For example, in 2017, adding hourly storage could improve capacity utilization from 51% to 58%. One week's duration of storage would improve it to 68%.

Scenario notes

2030

- In 2030, being able to shift energy across a *day* reduces back-up capacity by 16%, increasing utilization from 40% to 47%.
- Being able to shift energy across a *month* could reduce back-up capacity by a further 26 percentage points to 58%, increasing utilization of that capacity further to 66%.

2040

- In 2040, being able to shift energy across a *day* reduces back-up capacity by 23%.
- Being able to shift energy across a *month* could reduce back-up capacity by a further 30 percentage points to 47%, increasing utilization further to 40%
- Being able to shift energy across a *quarter* could see an additional 13% of non-wind/solar generation assets become redundant. This would increase back-up capacity utilization to 46%.

Nordics: overview of scenarios and issues

Analysis of a high-renewables power system in the Nordics

Overview of issues

The Nordic power system is fundamentally different to that of the U.K. and Germany, analysed in previous sections of this report. Therefore, many of the challenges that we see in these other regions do not show up in the Nordics.

1. The Nordics already have unrivalled clean, cheap and flexible resources

- The Nordics have abundant hydro resources that, in combination with nuclear power, supply the vast majority of electricity in the region.
- This combination is not only low-carbon and cheap, but also well-suited to deal with the volatility of demand and its corresponding ramping requirements.
- As such, the Nordics have little incentives to alter their power system except to replace the small amount of installed fossil capacity.

2. There is limited potential for wind and solar energy

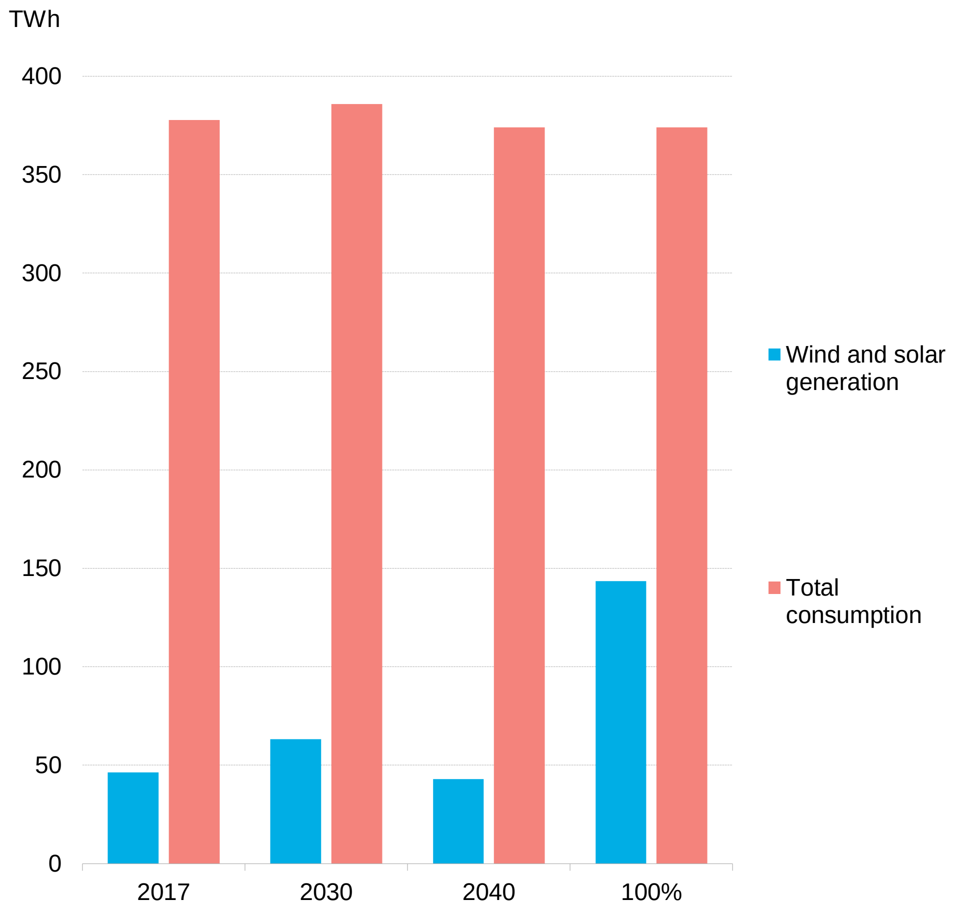
- The Nordic's sparse solar resource, in combination with the existing high penetration of low-carbon generation and decreasing demand, leaves little room for wind and solar energy.
- Wind and solar generation plays a small role in the Nordics, and is expected to supply less than 20% of total system demand even in the best months in 2030 and 2040.
- Therefore, curtailment of renewables at a system level is not forecast to occur in the Nordics. This means there is no case for shifting excess wind and solar generation across different time periods.

3. System volatility is largely unaffected

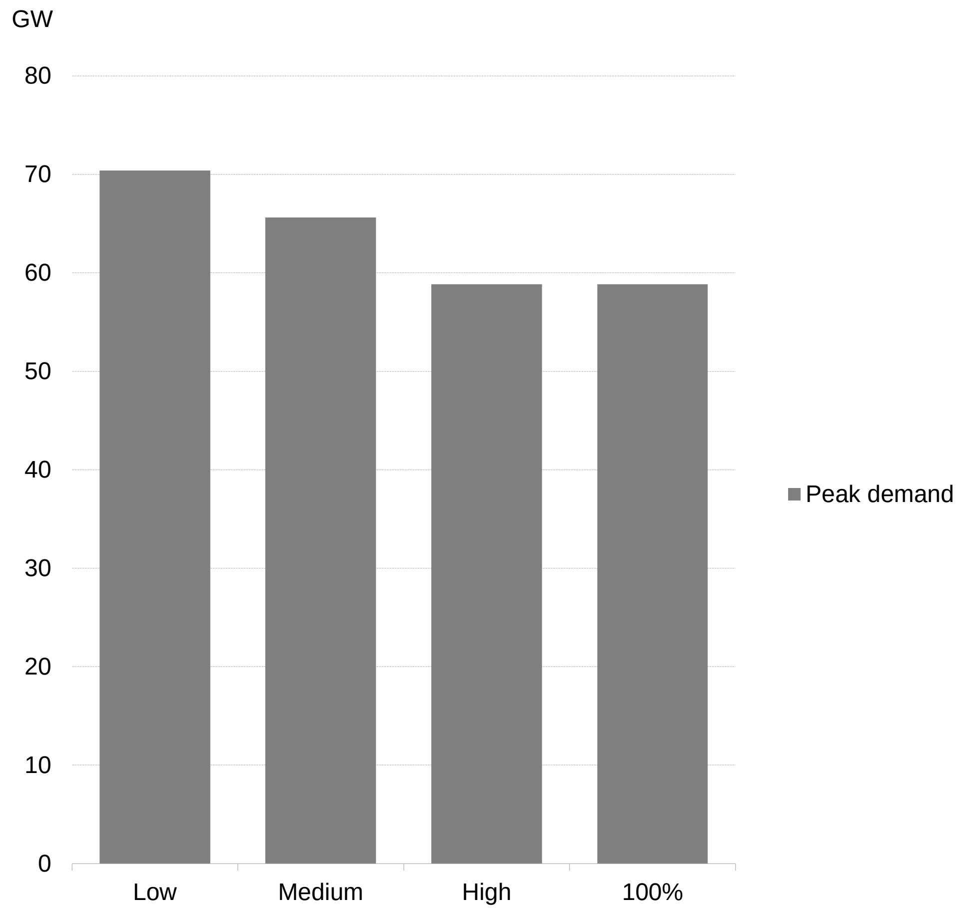
- The relatively small penetration of variable renewables means that the volatility of generation from these sources does not surpass existing demand volatility, except occasionally in the most extreme scenario.
- Thus, Nordic hydro's flexibility is more than capable of meeting demand even during the most extreme periods of wind and solar generation.

Four scenarios used in this analysis

Annual generation



Peak demand



Four scenarios used in this analysis

About the scenarios

- For our analysis of the Nordic flexibility gap, we looked at four scenarios* for wind and solar penetration, which we labelled:
  1. 2017
  2. 2030
  3. 2040
  4. 100%
- The first three scenarios (2017, 2030 and 2040) model a Nordic system with wind and solar penetration equivalent to these respective years in the BNEF New Energy Outlook forecast.
  - These scenarios explore what the flexibility gap would look like for the Nordics, if the renewable energy deployments modeled in New Energy Outlook were to come true.
  - The remainder of the generation stack (non-wind and solar) is simplified to a single resource which we call ‘other generation’.
- In the fourth scenario, ‘100%’, there is enough hydro, wind and solar generation to meet annual electricity demand.
  - This is not an economically modeled scenario, unlike the 2017, 2030 and 2040 scenarios which are outcomes of the New Energy Outlook. It is only included to illustrate an extreme case.
  - This scenario is different from the 100% scenario used in the Germany and U.K. studies, as it includes hydropower.

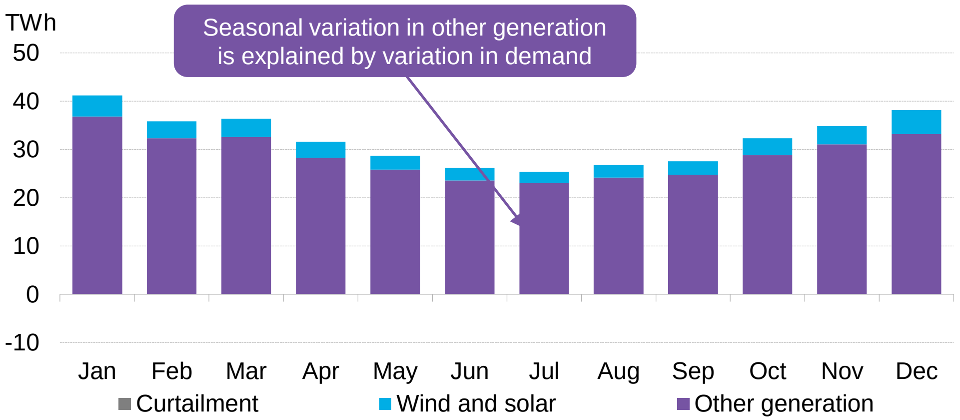
Note: we use ‘scenarios’ here to mean future penetrations of wind/solar – not alternative trajectories for the energy system. They are different points on the same trajectory.

Key figures used in each scenario

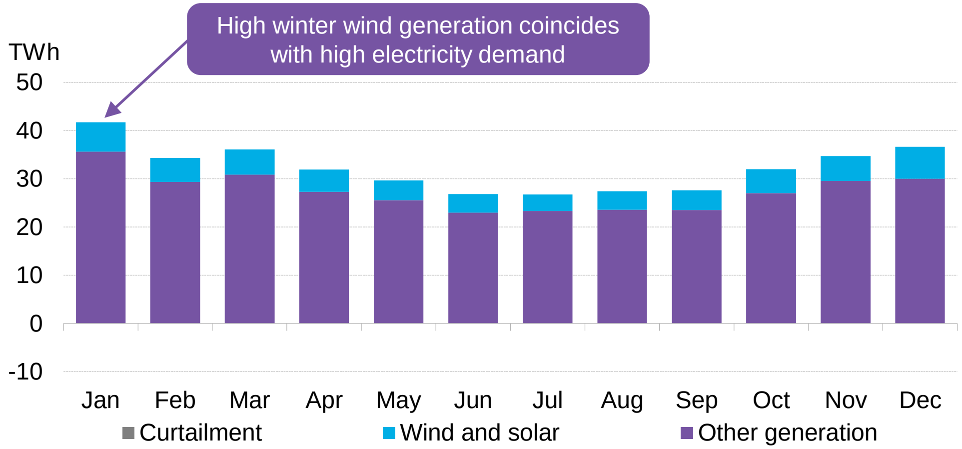
Scenario	2017	2030	2040	100%
Total demand (TWh)	378	386	374	374
Peak demand (GW)	70	66	59	59
Share of demand met by wind and solar (%)	10%	15%	11%	35%
Curtailment (TWh)	0	0	0	0
Onshore wind capacity (GW)	14	15	8	25
Offshore wind capacity (GW)	2	5	4	7
Solar PV capacity (GW)	1	3	6	19

Monthly generation

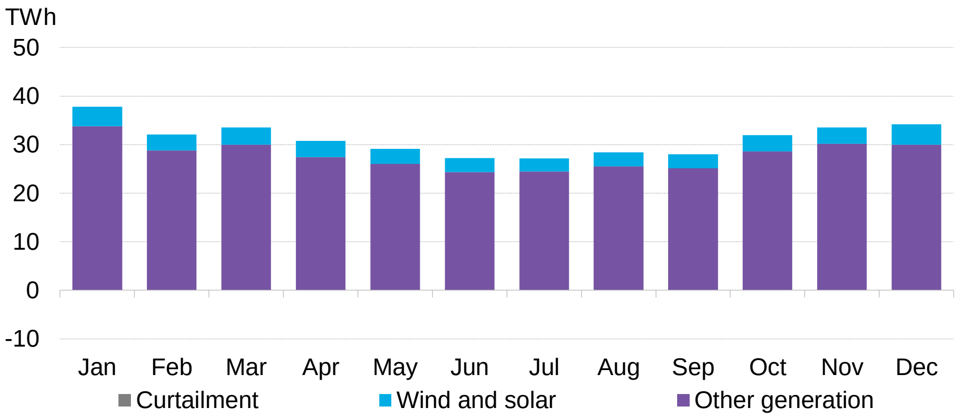
2017



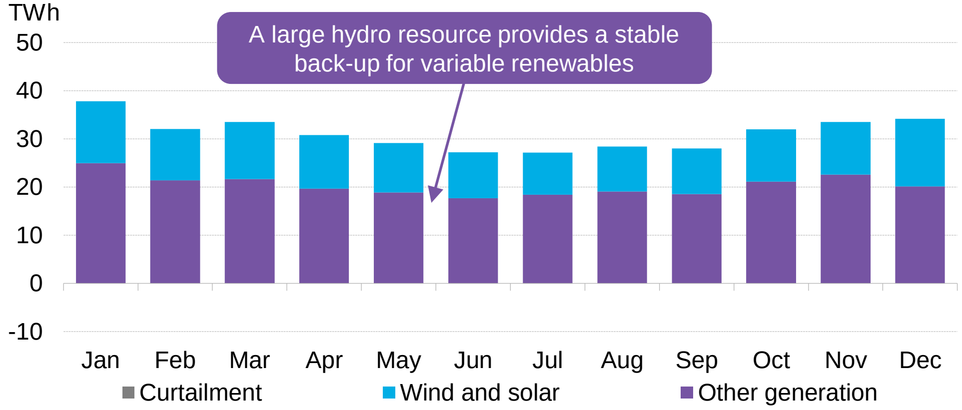
2030



2040



100%



Note: other generation includes all form of generation besides wind and solar, and can also be interpreted as 'net demand' – total demand net of wind and solar generation.

Monthly generation

Key trends

The charts above show how much of demand is supplied by wind/solar or other resources, at ***monthly*** granularity, for each scenario.

Two dynamics are apparent in the charts:

- **Highly seasonal electricity demand**: with its northern location, electricity consumption is highest in the winters. In the summer, consumption falls, and in some months it can be as little as 62% of the winter high.
- **High hydro generation reduces the need for variable renewables**: a large, inexpensive hydro fleet leaves little space for wind and solar generation. As a result, these two technologies rarely meet more than 11% of monthly demand in 2017 and 16% in 2030.

Scenario notes

2017

- Demand seasonality from winter to summer means monthly consumption can be as high as 41TWh and as low as 25TWh.

2030

- Wind additions drive up variable renewable generation in the winter months to around 7TWh.

2040

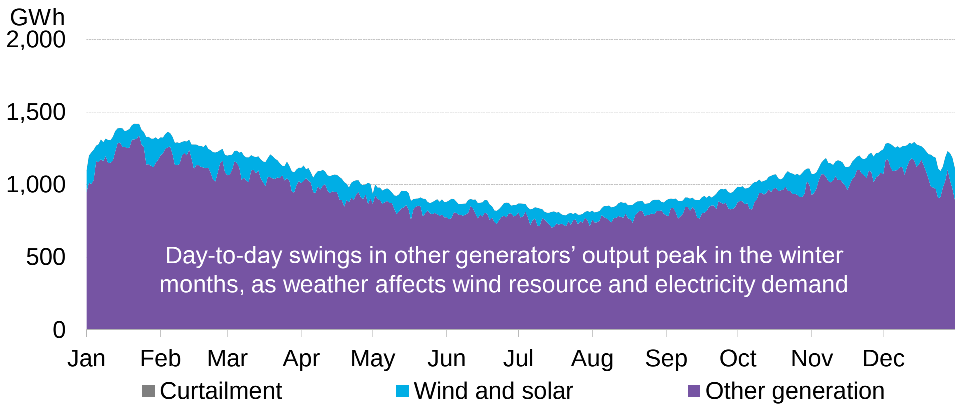
- Nordic variable renewables capacity shrinks over 2030-40, and so does output from these sources.
- Increasing electric vehicle demand, combined with falling overall demand, means the winter-to-summer consumption spread narrows to 11TWh.

100%

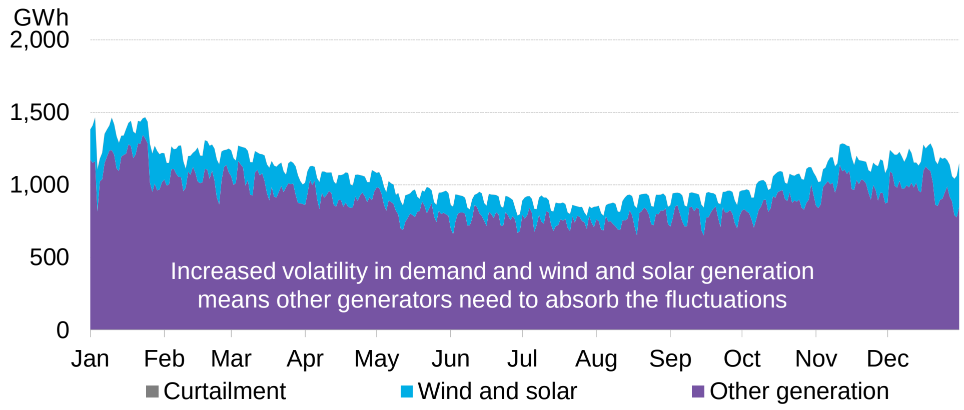
- Other generators – hydro in this case – provide a stable output around the year.
- Variable renewables have a seasonality that coincides with that of electricity demand.

Daily generation

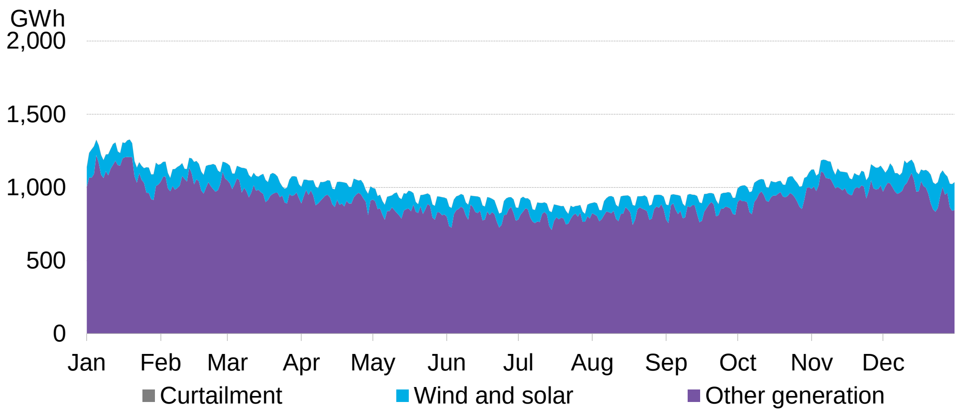
2017



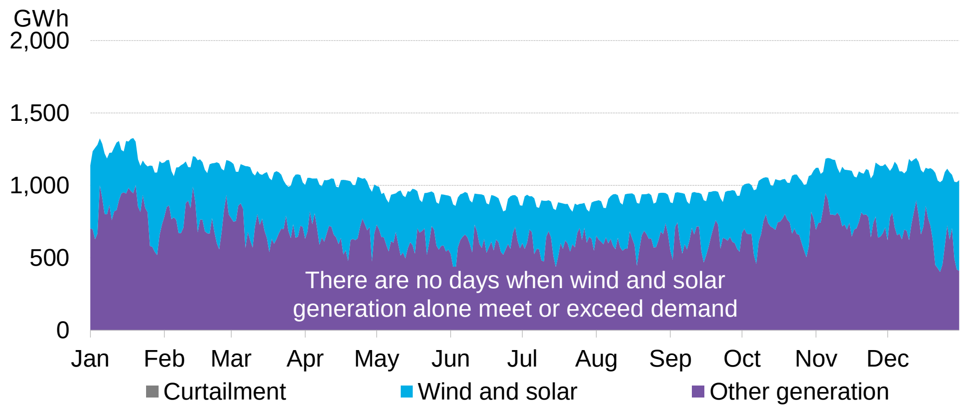
2030



2040



100%



Daily generation

Key trends

The charts above show how much of demand is supplied by wind/solar or other resources, at ***daily*** granularity, for each scenario.

Looking at the daily curve reveals a more detailed picture. The two main dynamics are:

- **Variability is highest in winter months**: demand variability is high in the winter months, when changes in weather drive shifts in consumption. This combines with wind output volatility, forcing other generators to absorb the changes.
- **Wind and solar never supply more than 61% of demand**: even in the hypothetical 100% scenario, hydro generation puts a floor on wind and solar output.

Scenario notes

2017, 2030, 2040

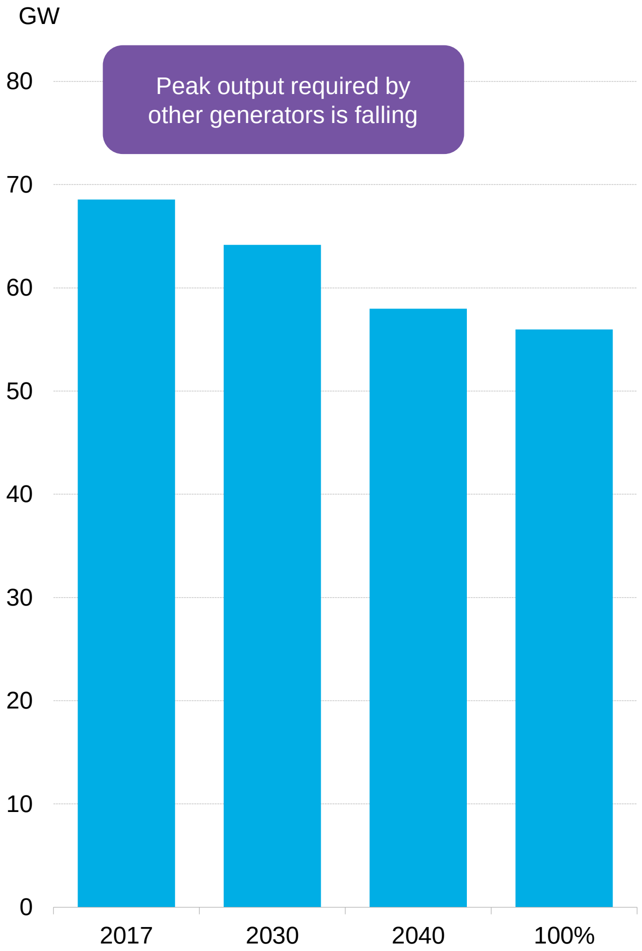
- Day-to-day swings in demand, which can be as high as 357GWh, are much more significant than even the biggest swings in wind and solar generation of 134GWh. Though these two occasionally combine, the largest required swings in generation from other sources is just 348GWh, occurring in 2030 – nearly three times more than in 2017.

100%

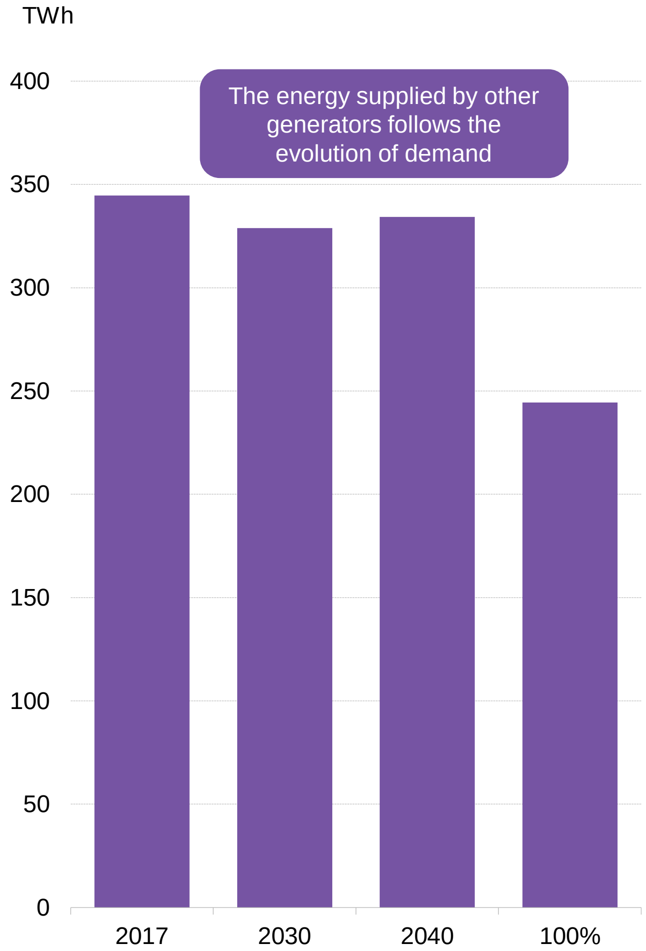
- Only in this scenario does day-to-day variability from wind and solar exceed day-to-day demand variability, requiring more flexible behavior from the installed hydro capacity.

Back-up capacity & declining utilization

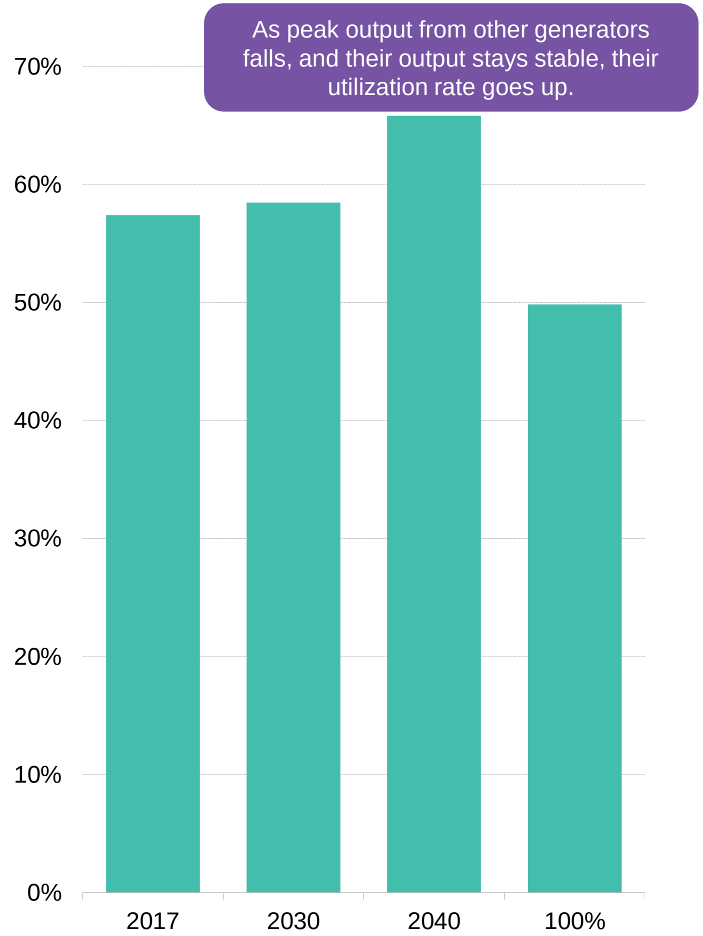
Peak output of ‘other generators’



Energy generated by ‘other generators’



Utilization of ‘other generators’



Back-up capacity & declining utilization

Key trends

- **In all scenarios, there are some hours when most of demand has to be met by other (non-wind/solar) sources.** As a result, between 56GW and 69GW of back-up are needed. These can be provided by dispatchable generation, or other sources such as interconnectors, energy storage and demand response.
- **Other generators maintain their dominant position in the Nordic market.** With a large hydro fleet, and little need for wind and solar, other generators on average meet around 82% of demand.
- **This keeps the utilization rate of other plants stable and relatively high.** Today, non-wind/solar generators run at around 57% utilization, and this is expected to increase to 58% in 2030, and 66% in 2040.

Scenario values

Scenarios	2017	2030	2040	100%
Peak output of other generators (GW)	69	64	58	56
Energy supplied by other generators (TWh)	345	329	334	244
Utilization of other generators (%)	57	58	66	50

System volatility

Distribution of hourly ramp rates across the year

System volatility

Key trends

The chart above shows how often 'other resources' (non-wind/solar) in the system have to ramp up and down, to accommodate hourly fluctuations in demand and wind/solar output. This is shown as a box plot illustrating the distribution of all the hourly ramp rates in a year.

- Typically, as wind and solar are added to the system, other sources have to ramp up and down more quickly, and more often.
- **Demand drives volatility**: with relatively low levels of wind and solar penetration compared to Germany or the U.K., most variations in output from other generation in the Nordics are driven by changes in demand.
  - Nordic demand is more volatile in the winter, changing by as much as 11GW over the course of a day. This volatility halves over shoulder months.
- **Volatility decreases**: as the Nordic system replaces wind with rooftop solar systems, extreme volatility events actually reduce in magnitude, falling to less than 5GW.
- The chart above only addresses hourly changes in demand and wind/solar output. It does not account for intra-hour fluctuations, for example to manage forecasting errors, or to maintain system frequency.

Scenario notes

2017

- The highest ramp-up is around 8GW in an hour, and the highest ramp-down is around 6GW/hour
- This corresponds to 10% of the region's hydro fleet turning on or off in an hour.

2030

- The highest ramp-up is around 6GW/hour and the highest ramp-down is 11GW/hour

2040

- The highest ramp-up shrinks to 5GW in an hour, and the highest ramp-down is around 3GW/hour

Nordics: hourly and daily variability

Analyzing hourly and daily issues

Managing hourly and daily variability

This section explores the short-term dynamics of a high-renewables system in the Nordics, focusing on issues that arise at the ***hourly*** and ***daily*** horizon. To do so, we have applied five years of historical solar/wind production data to each scenario.

Evolution

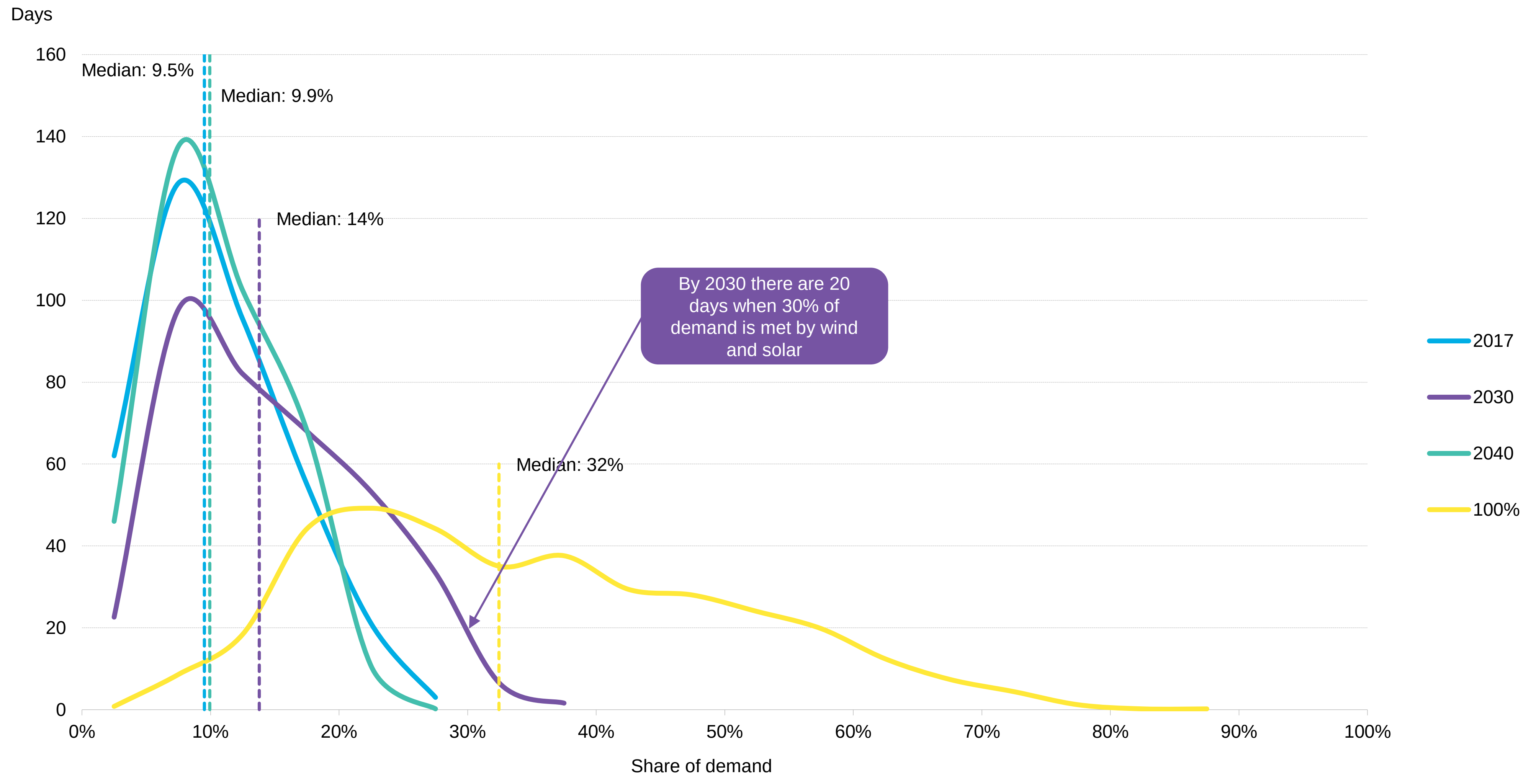
- Wind and solar energy never exceed total demand in 2030 or 2040.
  - Curtailment, or 'wasted' energy, due to wind and solar output exceeding demand, will not become an issue in the Nordics. (These figures do not account for grid and other constraints between and within different parts of the Nordic grid, which could lead to curtailment taking place regardless.)
- Overall system volatility is not a major challenge.
  - With limited growth in wind and solar in the Nordics, volatility does not change significantly from current levels, and is largely driven by demand patterns.
  - According to our modeling, in 2017 the maximum ramp rates are 8GW/hour up and 6GW/hour down. This represents about one-sixth of the Nordic hydro fleet turning on or off in an hour.
  - By 2040, the highest ramps will be 5GW up and 3GW down – some 37-50% lower than today.

Opportunities

- The vast availability of hydro resources is well-suited to dealing with the ramping requirements of the Nordics. However, local flexibility resources could still be required in case of volatility either in regions remote from hydro stations, or in regions connected via occasionally-congested transmission lines.

Variable renewable generation distribution

Number of days for which renewable generation makes up X% of demand



Source: Bloomberg New Energy Finance

Variable renewable generation distribution

Key trends

The chart above shows how often wind and solar account for a certain proportion of daily demand. For example, the blue curve shows that in 2017, wind and solar could account for 10% of demand on roughly 120 days of the year, but they rarely account for more than 20% of demand in a day.

- As the proportion of wind in the system grows by 2030, the curve flattens. Variable renewables increasingly meet more than 20% of demand, but rarely go above 30%.
- By 2040, retiring wind combined with rooftop solar additions means variable renewables reduce their share of demand met. Even in their highest output days, they struggle to meet more than 30% of energy needed.
- Even in the hypothetical scenario of 100% renewables (variable and hydro), wind and solar generation contributes on average around 30% of demand on a daily basis. The daily share of variable renewable generation never exceeds 90%.
- The next few pages explore these trends by showing hourly data for typical and extreme (high- and low-renewable) days.

Scenario notes

2017

- On a typical (median) day, wind and solar generate enough to meet 10% of demand.
- Wind and solar occasionally meet more than about 20% of demand in a given day. On very rare occasions they reach 30%.

2030

- On a typical (median) day, wind and solar generate 14% of demand.
- Over almost 30% of the year, they meet around 10% of daily electricity demand.
- Variable renewables never meet more than 40% of demand.

2040

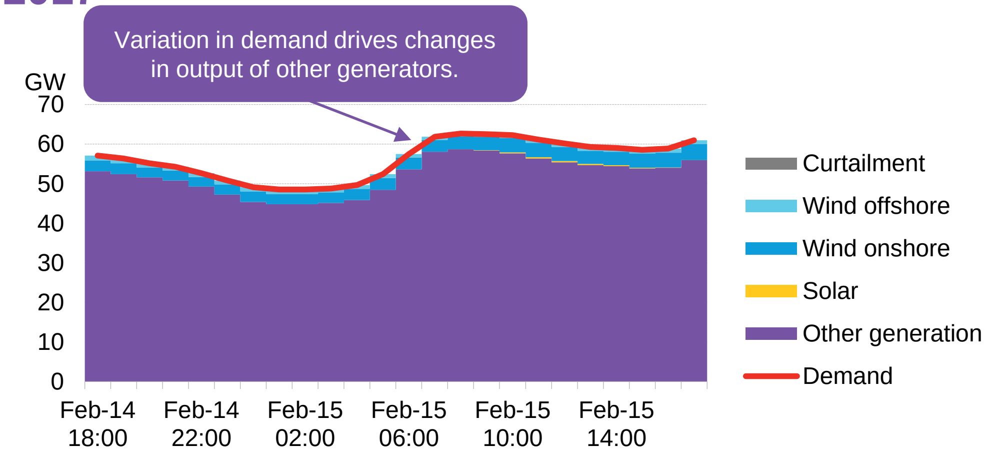
- On a typical (median) day, wind and solar generate 10% of demand.
- There are around 46 very low days, when variable renewables meet less than 5% of demand.
- Wind and solar never contribute more than 30% of daily demand needs.

100%

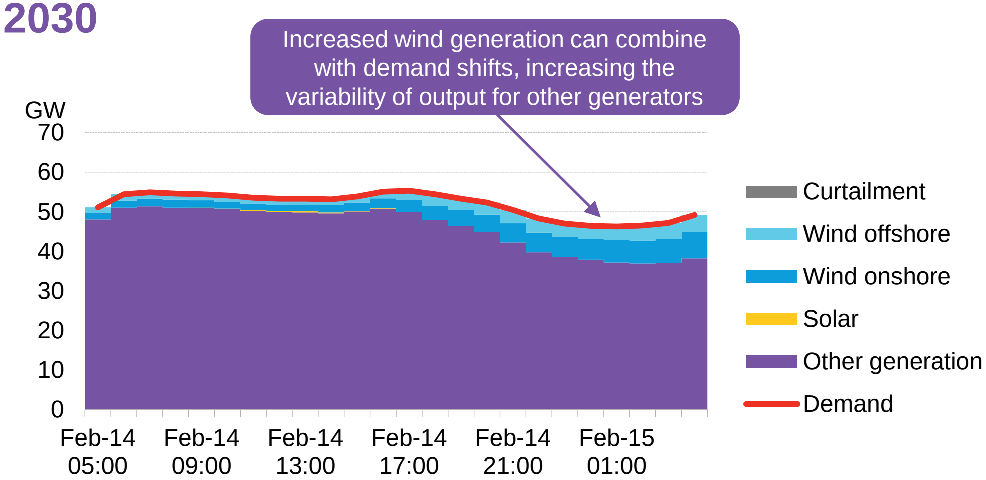
- In the most extreme case, wind and solar can generate up to 80% of daily energy demand.

Median wind and solar 24-hour period

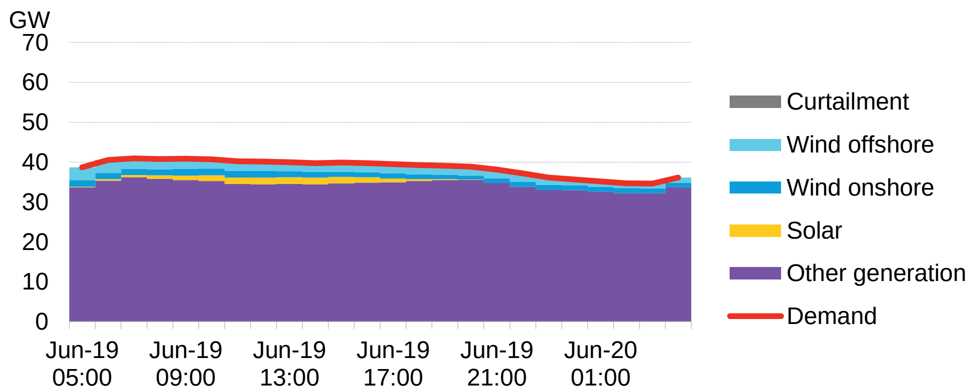
2017



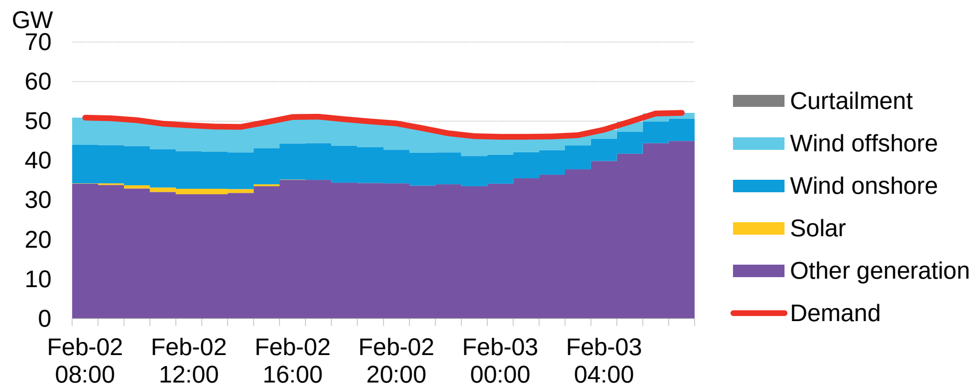
2030



2040



100%



Note: definition of the median renewable 24 hour period: 50% of 24-hour periods in the year have a higher share of renewable generation and 50% of 24-hour periods in the year have a lower share of renewable generation. These are 24-hour periods, not calendar days – so there are 8,736 24-hour periods in a year.

Median wind and solar 24-hour period

Key trends

The charts above show hourly production and demand for the *median day (by wind and solar share)* in each scenario. The purple 'other generation' columns show what other energy sources must provide in order to match hourly demand, after wind and solar production are accounted for.

- The Nordic system deploys little wind and solar capacity, with other generation retaining an important system role in all future years.
- Temporary increases in wind output can raise system volatility and require other generation to flex. Nonetheless, demand remains the main driver of hour-to-hour changes in their output.
- The maximum output required from other generation ranges from 61GW in the 2017 scenario, to 48GW in the 2030 and 2040 scenarios, and 35GW in the 100% case.
- As wind and solar shares remain low, there are no occurrences of over-generation and curtailment.

Scenario notes

2017

- Other generation adjusts gradually to account for demand changes and modest shifts in wind and solar production.

2030

- Upswings in wind output can coincide with falls in demand, forcing other generation sources to reduce their output by as much as 14GW over the course of the median day.

2040

- As wind capacity retires and some rooftop solar replaces it, system volatility decreases. Demand remains the main source of system variations, driving changes in 'other generator' output.

100%

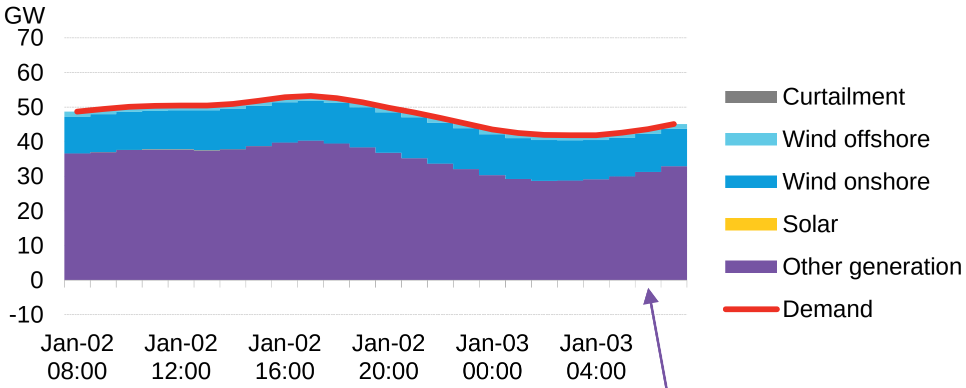
- The median day in the extreme case falls on a winter day in February. Over the day, onshore and offshore wind combined meet around 27% of demand. 'Other generator' output stays flat until the end of the period, when wind output starts dropping.

Note: definition of the median renewable 24 hour period: 50% of 24-hour periods in the year have a higher share of renewable generation and 50% of 24-hour periods in the year have a lower share of renewable generation. These are 24-hour periods, not calendar days – so there are 8,736 24-hour periods in a year.

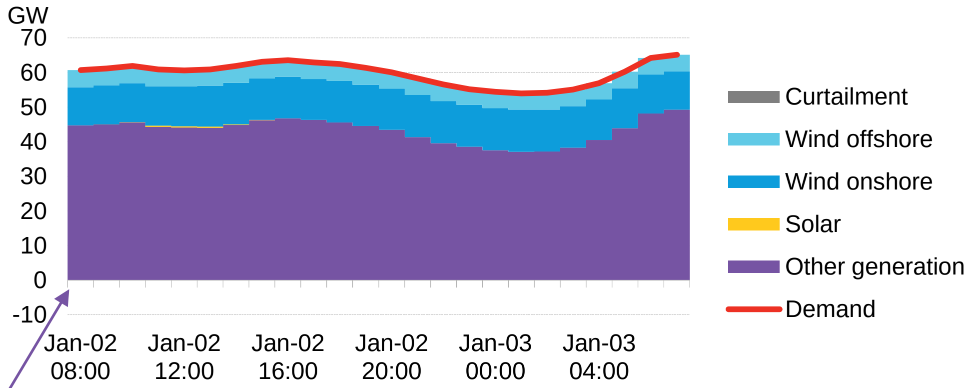
Nordics: hourly and daily variability

Highest wind and solar 24-hour period

Low

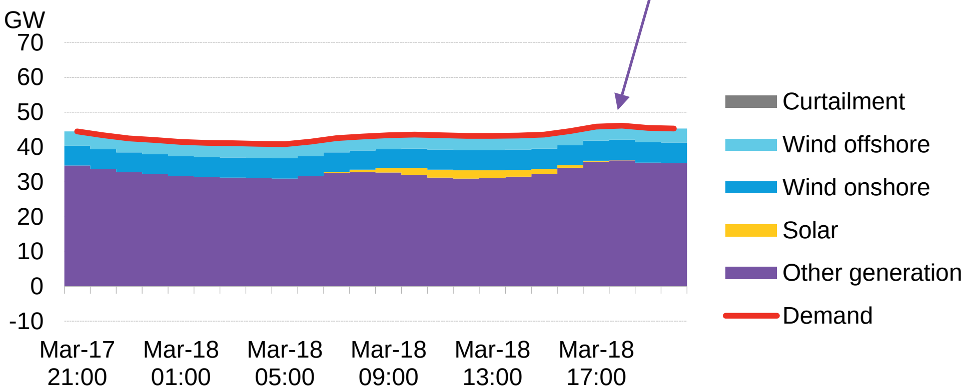


2030

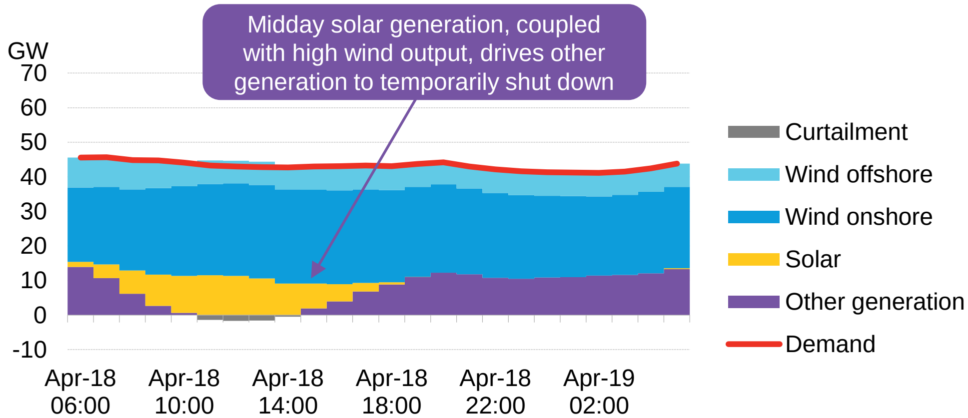


Demand drives system variability as wind generates with a steady profile

2040



100%



Note: 24-hour periods where wind and solar account for the highest share of demand in the year. These are 24-hour periods, not calendar days – so there are 8,736 24-hour periods in a year.

Highest wind and solar 24-hour period

Key trends

The charts above show hourly production and demand for the *highest day (by wind and solar share)* in each scenario. The purple ‘other generation’ columns show what other energy sources must provide in order to match hourly demand, after wind and solar production are accounted for. Grey shows curtailment, when wind and solar alone exceed demand.

Looking at the highest wind/solar production day allows us to see the most extreme daily dynamics at work.

- In all these examples of the highest wind/solar day, wind has a stable generation profile. As a result, variations in the system come from changes in demand, rather than variable renewable output.

Scenario notes

2017

- Over the high-variable-renewables period, wind puts out a stable 11GW per hour, meeting between 25% and 30% of hourly demand.
- Other generators change their output to adjust to variations in demand.

2030

- As the Nordic region does not add much variable renewable capacity, the picture in 2030 remains very similar to that in 2017.

2040

- With wind retiring, and solar taking its place, the 24-hour period of high wind and solar output shifts to March, when electricity demand is lower than in winter.
- Though midday upticks in solar output require other generators to flex their output, the volatility is significantly lower than that caused by changes in demand over winter months.

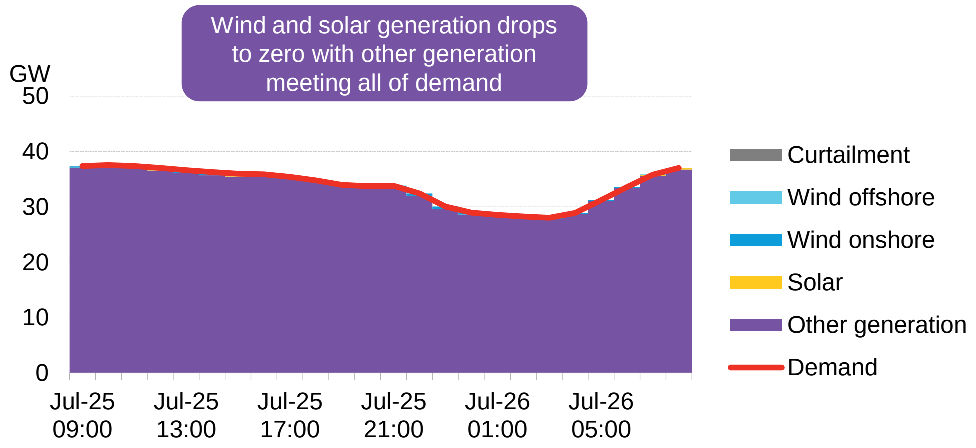
100%

- Wind generates at a stable output over the day, meeting more than two thirds of demand. As solar output picks up, total wind and solar generation just about exceeds supply and the other generators are required to shut down. Less than 1% of wind and solar output over the course of the day needs to be curtailed.

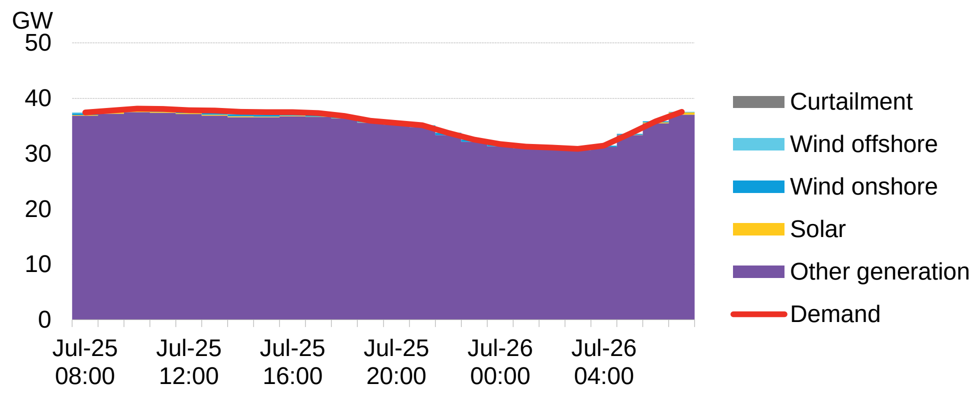
Note: 24-hour periods where wind and solar account for the highest share of demand in the year. These are 24-hour periods, not calendar days – so there are 8,736 24-hour periods in a year.

Lowest wind and solar 24-hour period

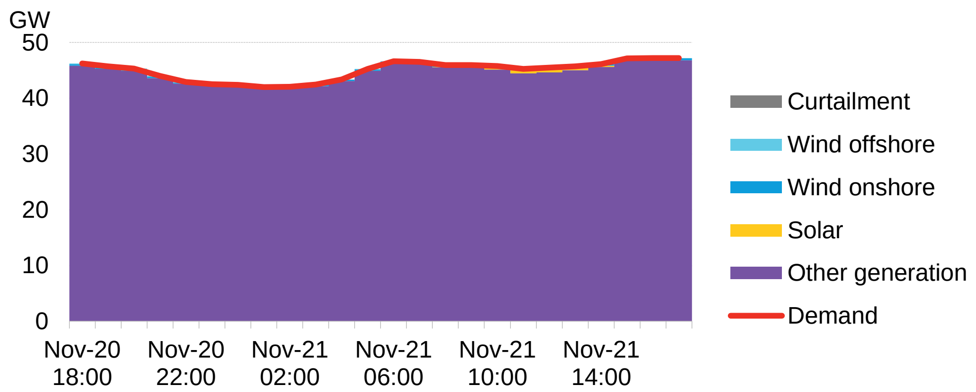
2017



2030



2040



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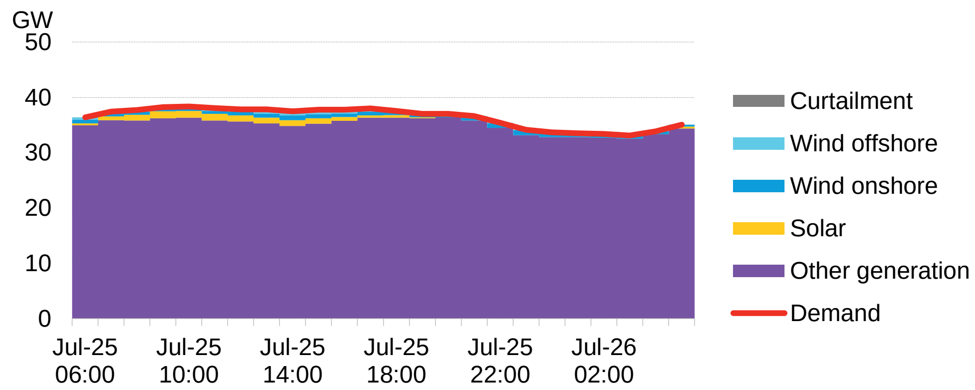


Note: 24-hour periods where wind and solar account for the lowest share of demand in the year. These are 24-hour periods, not calendar days – so there are 8,736 24-hour periods in a year.

Lowest wind and solar 24-hour period

Key trends

The charts above show hourly production and demand for the *lowest day (by wind and solar share)* in each scenario. The purple ‘other generation’ columns show what other energy sources must provide in order to match hourly demand, after wind and solar production are accounted for.

- Even with the addition of more wind and solar capacity, there will be days when variable renewables output will be close to zero. In the Nordics in 2040, this extreme occurs on a winter’s day when there is cloud cover and little wind.
- Over such days, other generating sources will have to meet almost all energy and power requirements.

Scenario notes

- In the 2030, 2040 and 100% scenarios, days with almost no wind and solar production are possible. This means that the peak output required by other generators over such days is driven exclusively by demand, rather than renewables.

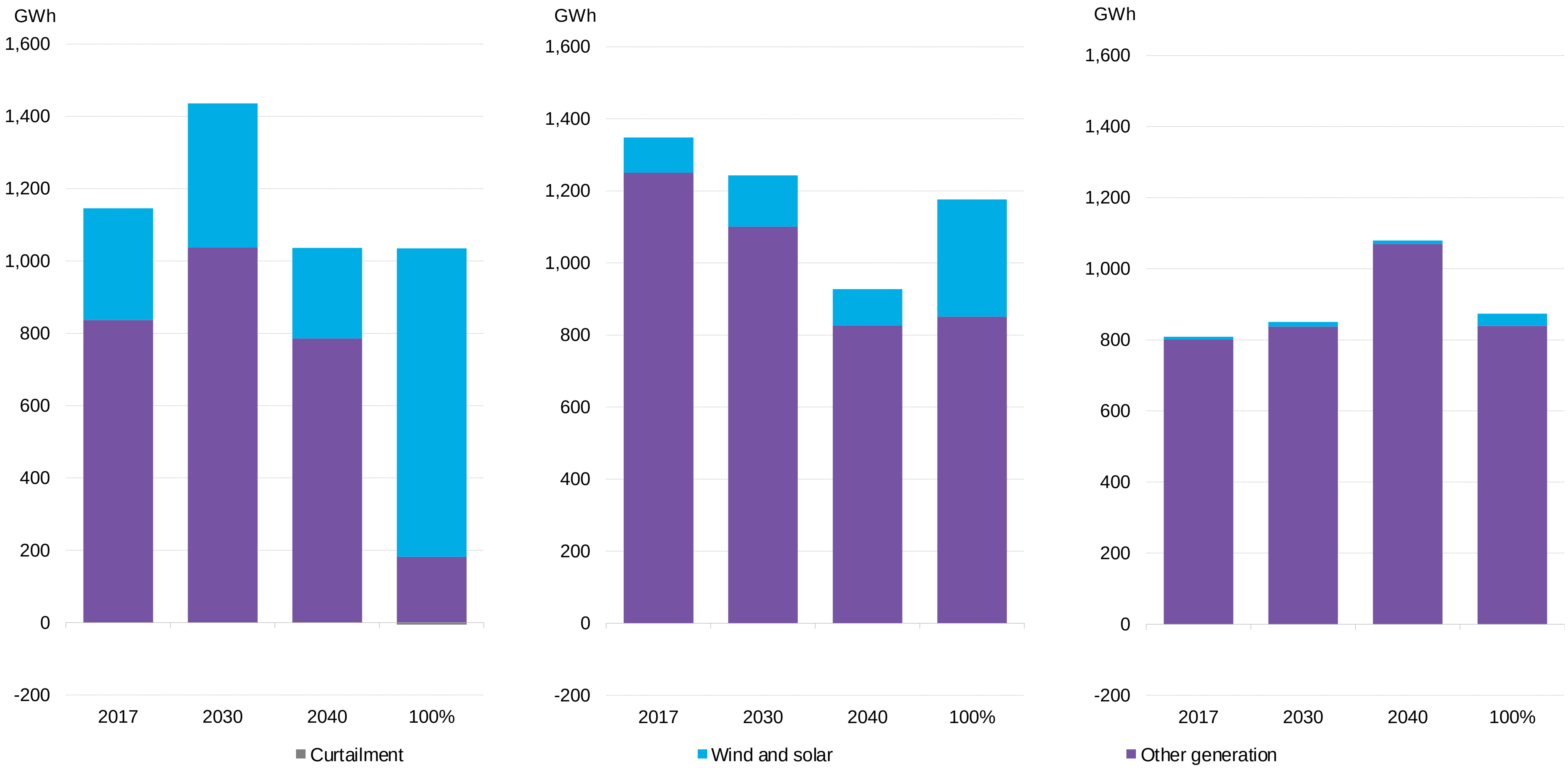
Note: 24-hour periods where wind and solar account for the lowest share of demand in the year. These are 24-hour periods, not calendar days – so there are 8,736 24-hour periods in a year.

Summary of challenges and opportunities

Highest renewables 24-hour period generation breakdown

Median renewables 24-hour period generation breakdown

Lowest renewables 24-hour period generation breakdown



Summary of challenges and opportunities

Evolution of the system

- **Wind and solar stays stable**: due to the region's vast installed base of hydro, wind and solar additions out to 2040 only replace previously existing capacity. As a result, across the 2017, 2030 and 2040 scenarios, the three characteristic days look very similar.
- **Other generators maintain high output**: even on the highest wind/solar output days, the need for other generation remains very similar to that in the low and median case for the 2017, 2030 and 2040 scenarios.
- **Low wind/solar output occurs outside of the winter:** Especially in the earlier years, most variable renewable capacity is wind rather than solar. As wind output peaks in the winter months, when demand is also high, periods of low renewables output coincide with low demand, outside of the winter.
- **Variable renewables output never exceeds 82%**: even in the 100% scenario, wind and solar contribute a maximum of 82% of total electricity needed over the day.

Key scenario values

	Metric	Low	Median	High
2017	Other generation (GWh)	801	1,250	837
	Wind and solar output (GWh)	8	98	309
	Wind and solar share	1%	7%	27%
2030	Other generation (GWh)	838	1,100	1,037
	Wind and solar output (GWh)	12	142	399
	Wind and solar share	1%	11%	28%
2040	Other generation (GWh)	1,070	826	786
	Wind and solar output (GWh)	10	101	250
	Wind and solar share %	1%	11%	24%
100%	Other generation (GWh)	839	851	182
	Wind and solar output (GWh)	34	325	853
	Wind and solar share	4%	28%	82%

Nordics: weekly, monthly and seasonal variability

Analyzing weekly to seasonal issues

Managing longer-term variability

This section explores the longer-term dynamics of a high-renewables system in the Nordics, focusing on issues that arise at the ***weekly to seasonal*** horizon.

Evolution

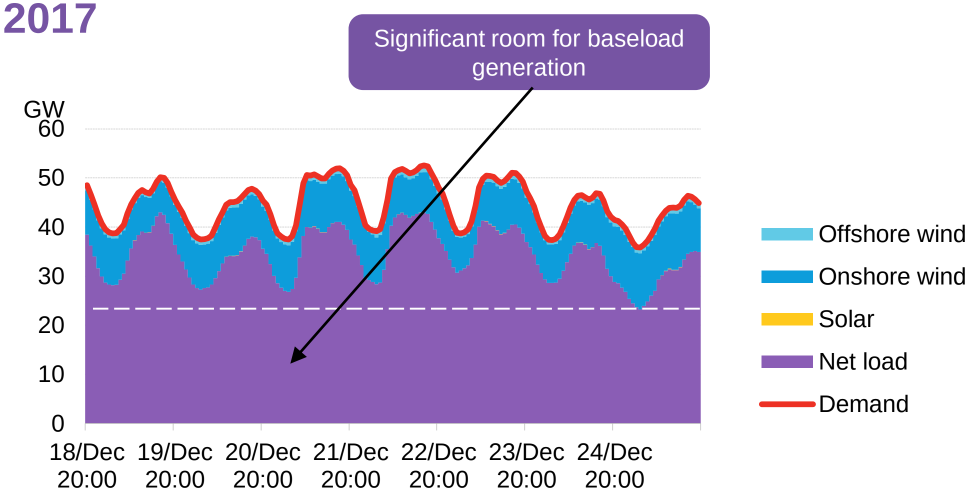
- For this section, we have again applied five years of past solar/wind production data to each scenario, in order to find the most extreme weeks and months.
- The Nordics market remains relatively unchanged, unlike other European power systems, which undergo massive shifts as wind and solar capacity grows.
  - The relatively small addition of wind and solar capacity will not have a significant impact on the overall structure and operation of the generation fleet, even during the most extreme periods.
  - Because hydropower is so dominant, a 78% renewable (11% solar and wind) scenario in 2040 is achieved without introducing large amounts of volatility and curtailment. There is still room for baseload resources that are always on.
- The periods of highest and lowest wind and solar output complement hydro resources.
  - The hydrological cycle in the Nordics is such that water inflow is at its lowest during winter, when water is mostly frozen, and at its highest during spring and summer, when snow melts.
  - The opposite is true of wind power, which is higher over the winter, when demand is high, and lower over the summer.
  - The complementary nature of wind and hydro makes wind a good fit for the Nordic power system.

Opportunities

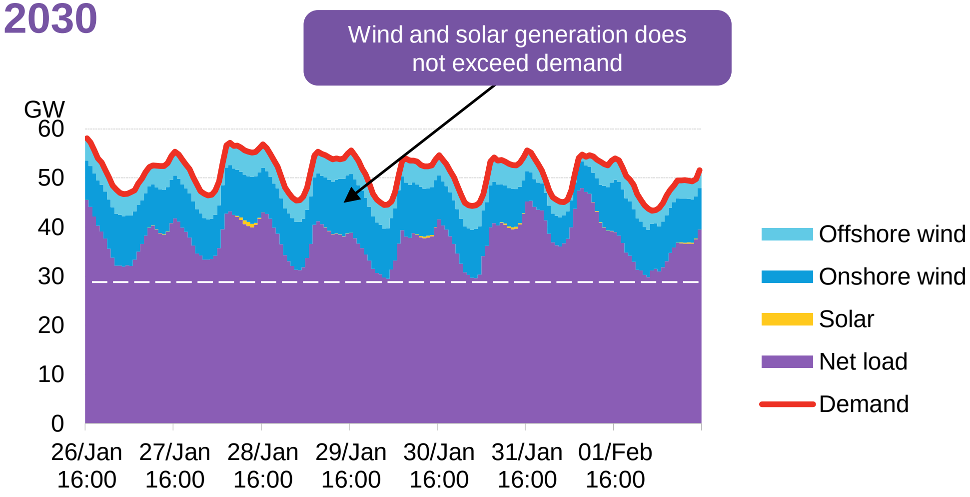
- Thanks to Norwegian and Swedish hydropower, the Nordics have the flexible resources required to accommodate variable renewables – and even have flexibility to spare.
- Although we have analysed the Nordics as a single market, in actual fact the majority of hydro resources are in Norway and Sweden.
- These resources allow the region as a whole to both achieve deep decarbonization, and introduce variable wind and solar capacity without encountering system flexibility issues.
- The Nordics are thus in a privileged position to be able to take advantage of cheap wind and solar, reducing the need for other types of capacity and energy – including additional storage technologies. (Note that this assumes strong interconnection between Nordic countries.)
- In fact, our analysis indicates that there is more than enough flexible hydro capacity to deal with the variability of wind and solar. This presents an opportunity for increased interconnections to other European countries such as the U.K. and Germany. Nordic hydro could then provide additional flexibility in those markets where wind and solar may reach much higher penetration rates.

Highest wind and solar output week

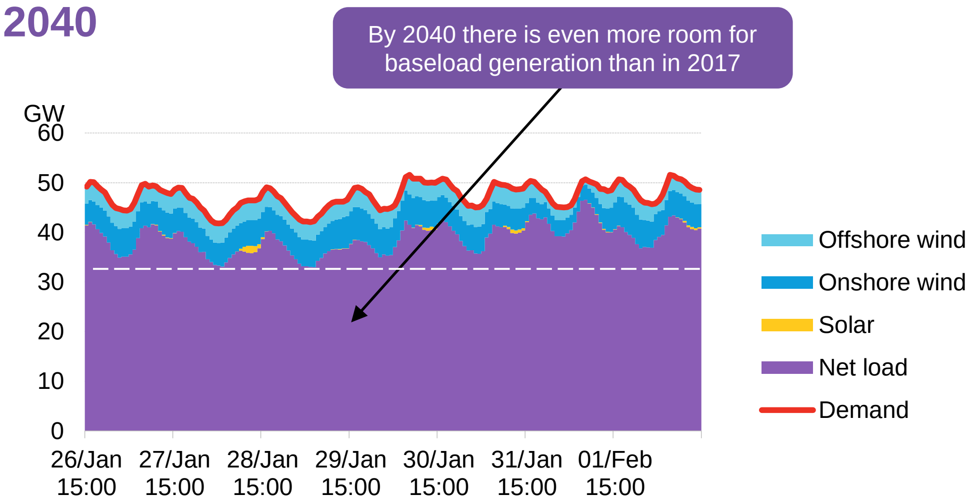
2017



2030



2040



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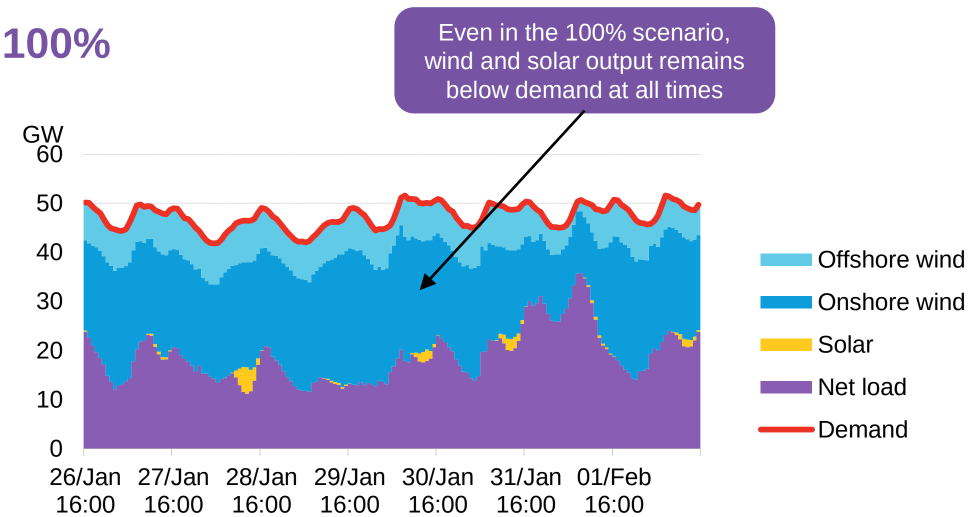


Note: a week is defined as a 168 hour period

Highest wind and solar output week

Key trends

The charts above show hourly production and demand for the *highest week (by wind and solar share)* in each scenario. The purple 'other generation' columns show what other energy sources must provide in order to match hourly demand, after wind and solar production are accounted for.

- In all scenarios, the highest week occurs in winter during a period of high winds and almost no sun.
- In general, the role of other generation remains unchanged to 2030 and 2040.
- However, the wind and solar mix varies from 2030, when there is six times as much wind capacity as solar, to 2040 – by which time solar capacity has doubled and wind halved.

Scenario notes

2017

- In 2017, there is a requirement for about 23GW of baseload generation, running flat out at steady output. Even during the periods of highest wind and solar output, there is a minimum level of other generation required.

2030

- By 2030, there are weeks where wind and solar generation supplies up to 26% of demand. But there is still plenty of room for technologies that need to run flat-out, such as nuclear power**.**

2040

- In 2040 other sources of generation are still required at all times during the highest wind and solar output weeks, supplying 82% of the energy consumed. Renewable generation never exceeds demand, even for an hour.

100%

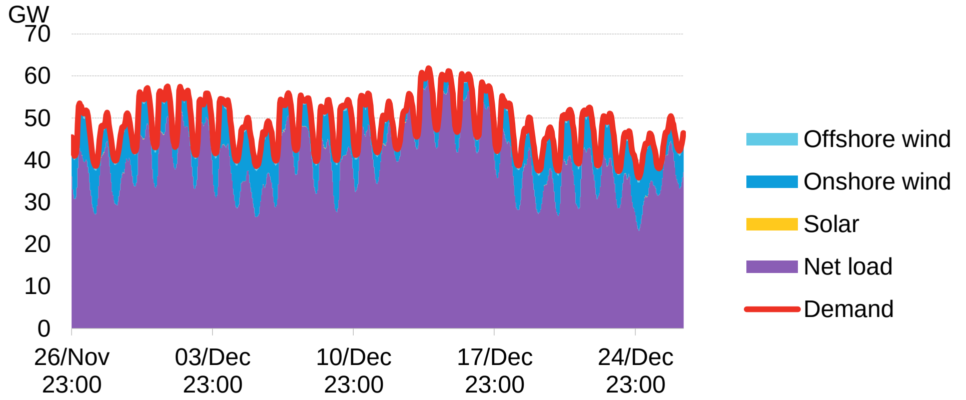
- Other resources are constantly needed even in the 100% scenario, where 60% of consumption comes from wind and solar energy. This shows that the system could accommodate even more variability, potentially contributing to the balancing of demand and supply in neighboring countries such as Germany.

Note: a week is defined as a 168 hour period, not a calendar week.

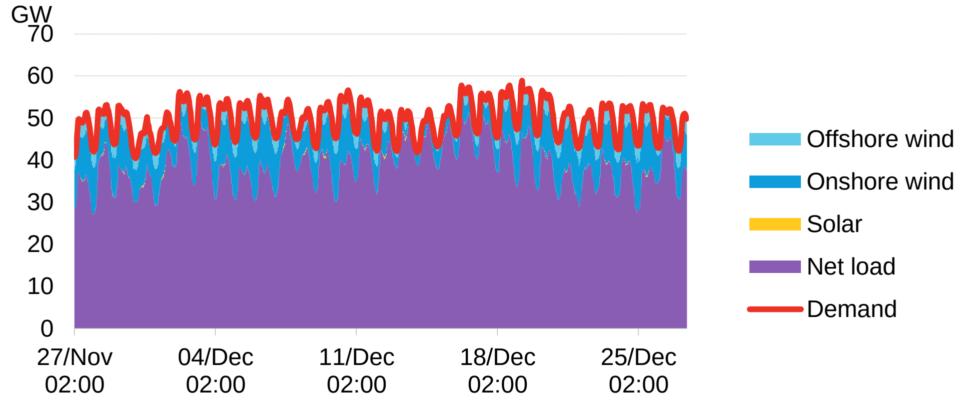
Nordics: weekly, monthly and seasonal variability

Highest wind and solar output month

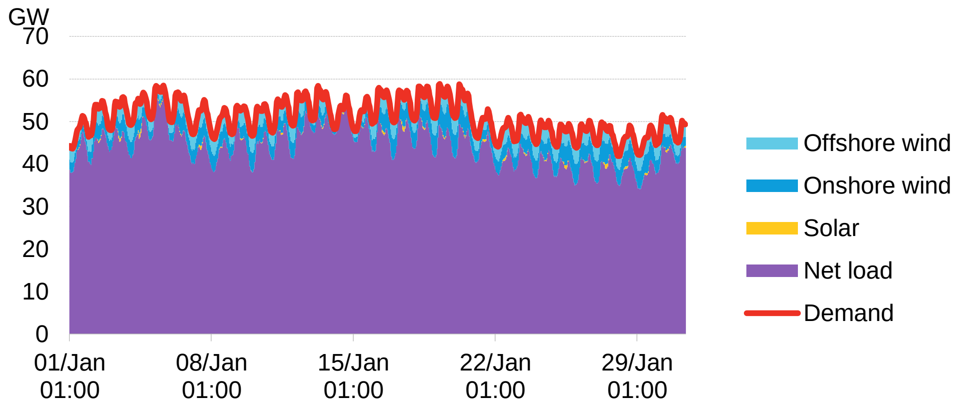
2017



2030



2040



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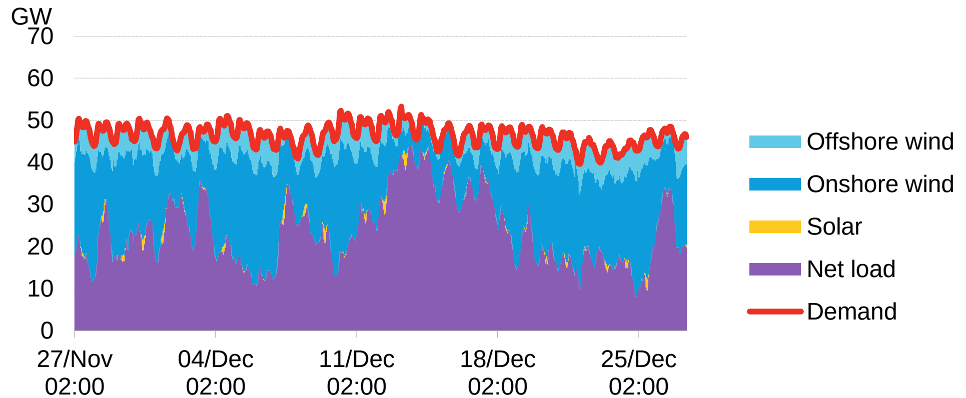


Note: a month is defined as a 730 hour period

Highest wind and solar output month

Key trends

The charts above show hourly production and demand for the *highest month (by wind and solar share)* in each scenario. The purple 'other generation' columns show what other energy sources must provide in order to match hourly demand, after wind and solar production are accounted for.

- We see similar trends for high wind/solar output months as we do at the one-week level. This implies that wind and solar generation does not present a seasonal challenge in the Nordics.
- Over these high-production months in 2030 and 2040, wind and solar energy still plays a secondary role, supplying less than a quarter of electricity consumed over the period.
- Other generation sources are needed in all scenarios, throughout the entire month. As a result, the need for baseload generation remains present through 2030 to 2040.
- At no point does wind and solar generation in the Nordics surpass system demand, even by 2040.

Scenario notes

2017

- As in the 'weeks' analysis, in 2017 there is a requirement for about 27GW of baseload generation, running flat out at steady output.

2030

- In 2030, wind and solar supply 21% of the electricity consumed during the month, similar to the situation in 2017. This leaves more than enough room for baseload generators.

2040

- Other sources of generation are constantly required during the highest wind and solar output months, supplying 87% of generation. Room for baseload is even higher than in 2017.
- There is no curtailment in the month.

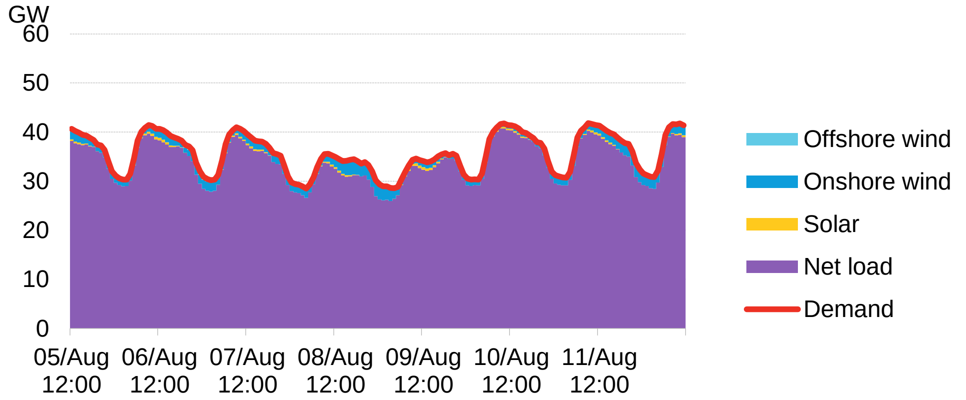
100%

- Other resources are needed in every hour even in the 100% scenario, where they supply about half of generation. There is no excess renewable energy across the month.
- As during the highest wind and solar output week, given enough interconnection, the system could provide flexibility to neighboring regions.

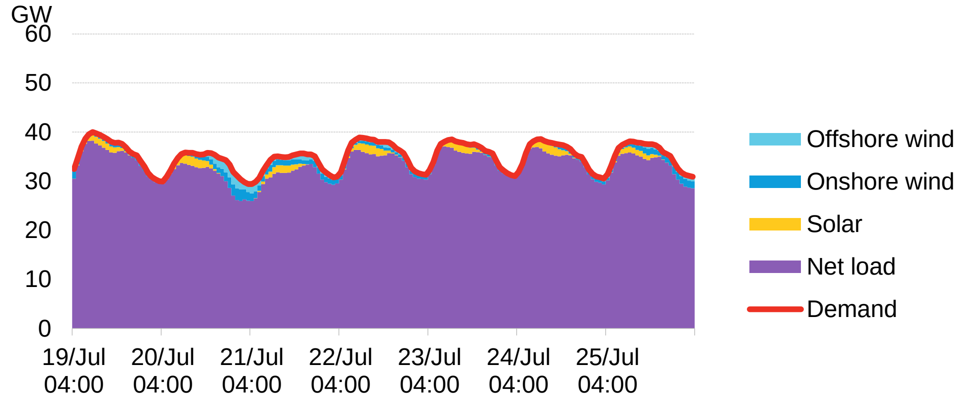
Note: a month is defined as a 730 hour period, not a calendar month.

Lowest wind and solar output week

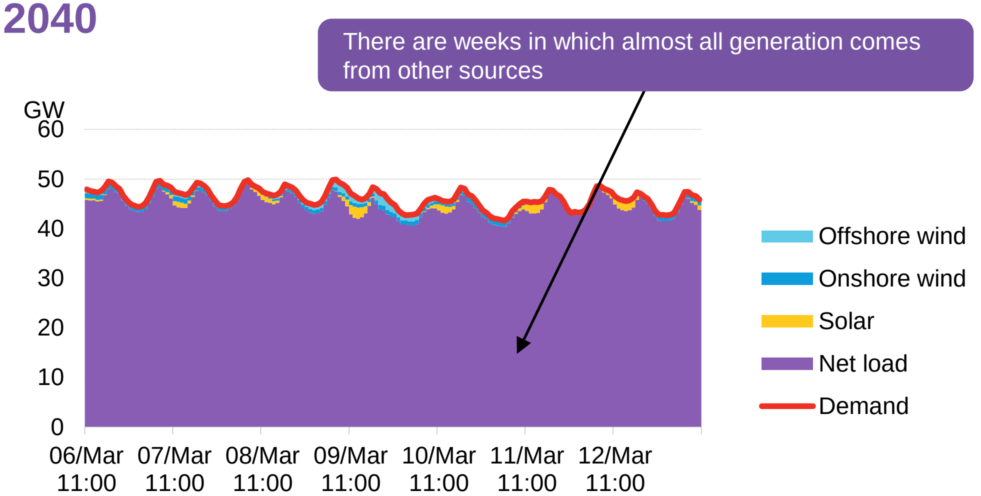
2017



2030



2040



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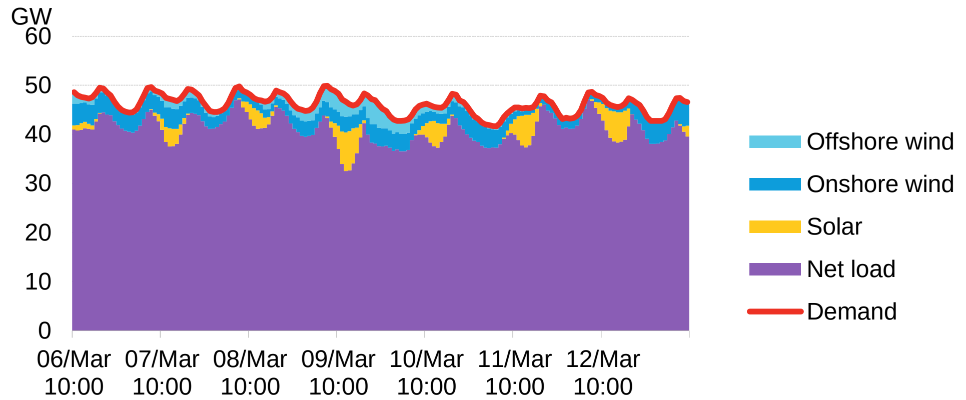


Note: a week is defined as a 168 hour period

Lowest wind and solar output week

Key trends

The charts above show hourly production and demand for the *lowest week (by wind and solar share)* in each scenario. The purple 'other generation' columns show what other energy sources must provide in order to match hourly demand, after wind and solar production are accounted for.

- In the Nordics, where solar capacity is very limited, minimum wind and solar generation happens from spring to autumn, when the wind resource is lowest.
- Across all scenarios, there are weeks when almost all generation has to come from other sources. These weeks see nearly no variable renewable energy generation.
- Low wind and solar weeks require about 95% of generation to come from other sources, even in 2030 and 2040.

Scenario notes

2017

- 95% of demand is met by non-wind/solar generators in this low week.

2030

- Despite the growth in wind and solar capacity, the lowest week in 2030 still sees 95% of demand met by other generators, the same as in 2017.
- On average, 34GW of other generation is online during this period.

2040

- Even in 2040, the lowest week still sees 97% of demand met by non-wind/solar generation.
- On average, 45GW of other generation is online during this week.

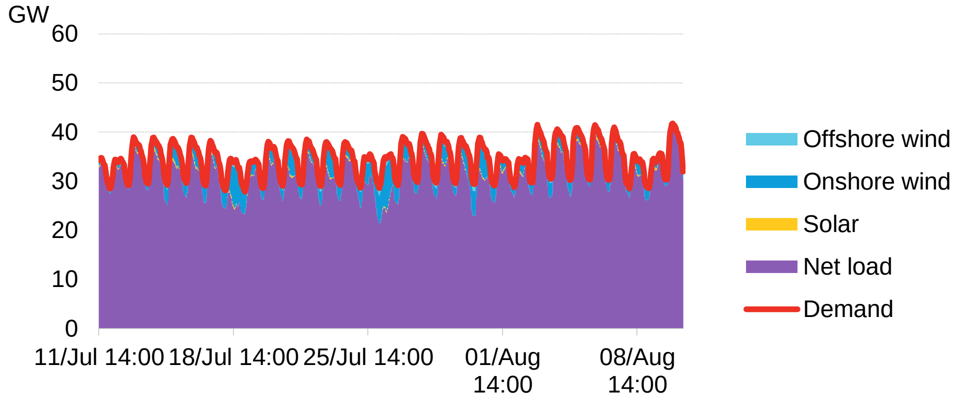
100%

- Even in this scenario, where there is enough wind and solar to supply annual power demand, there are weeks when other sources must meet as much as 88% of demand.

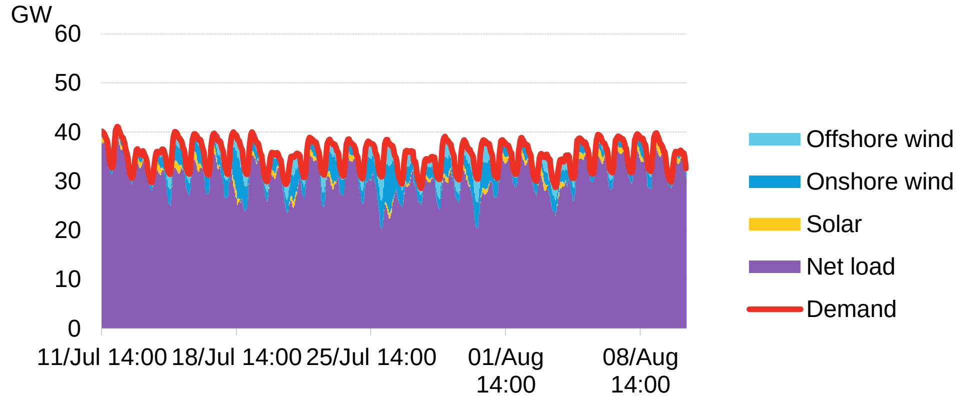
Note: a week is defined as a 168 hour period, not a calendar week.

Lowest wind and solar output month

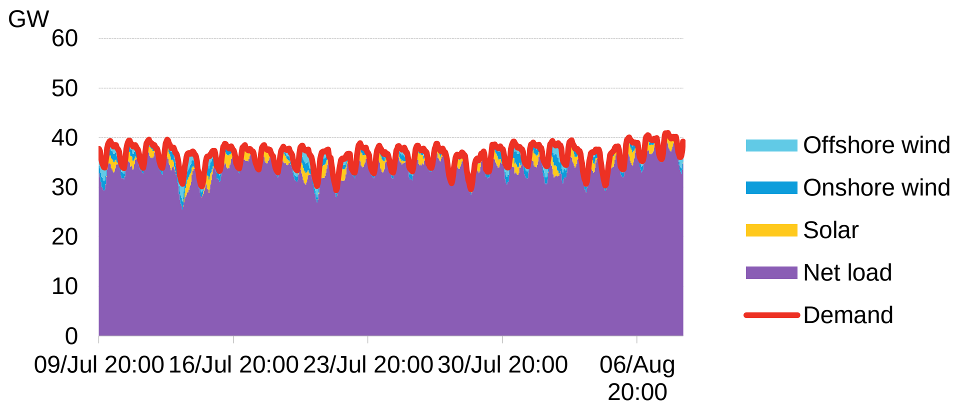
2017



2030



2040



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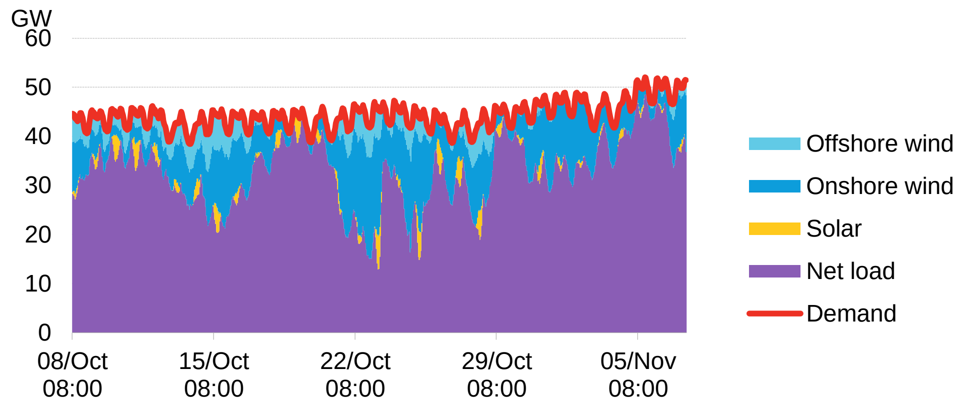


Note: a month is defined as a 730 hour period, not a calendar month.

Lowest wind and solar output month

Key trends

The charts above show hourly production and demand for the *lowest month (by wind and solar share)* in each scenario. The purple 'other generation' columns show what other energy sources must provide in order to match hourly demand, after wind and solar production are accounted for.

- Low wind and solar output periods can last for whole months, not just weeks at a time. Here we see month-long periods in summer and autumn where wind and solar production remain low.
- The amount of generation required from other sources declines from 91% to about 87% from 2017 to 2030, only to rise again by 2040 to about 93%, as wind capacity is decommissioned and more solar is deployed.

Scenario notes

2017

- 91% of demand is met by non-wind/solar generators across this month-long period of low variable renewable generation.

2030

- By 2030, low-variable-renewables months need almost as much support from other generators: they supply 87% of demand.
- On average, 31GW of 'other generation' is online during this period, but it needs to be flexible to account for changes in variable renewable production and demand.

2040

- In the low-wind/solar month in 2040, other sources need to supply a higher share (93%) of demand than in 2030. This is due to a reduction in installed wind and an increase in solar capacity.
- On average, 34GW of other generation is online during this week.

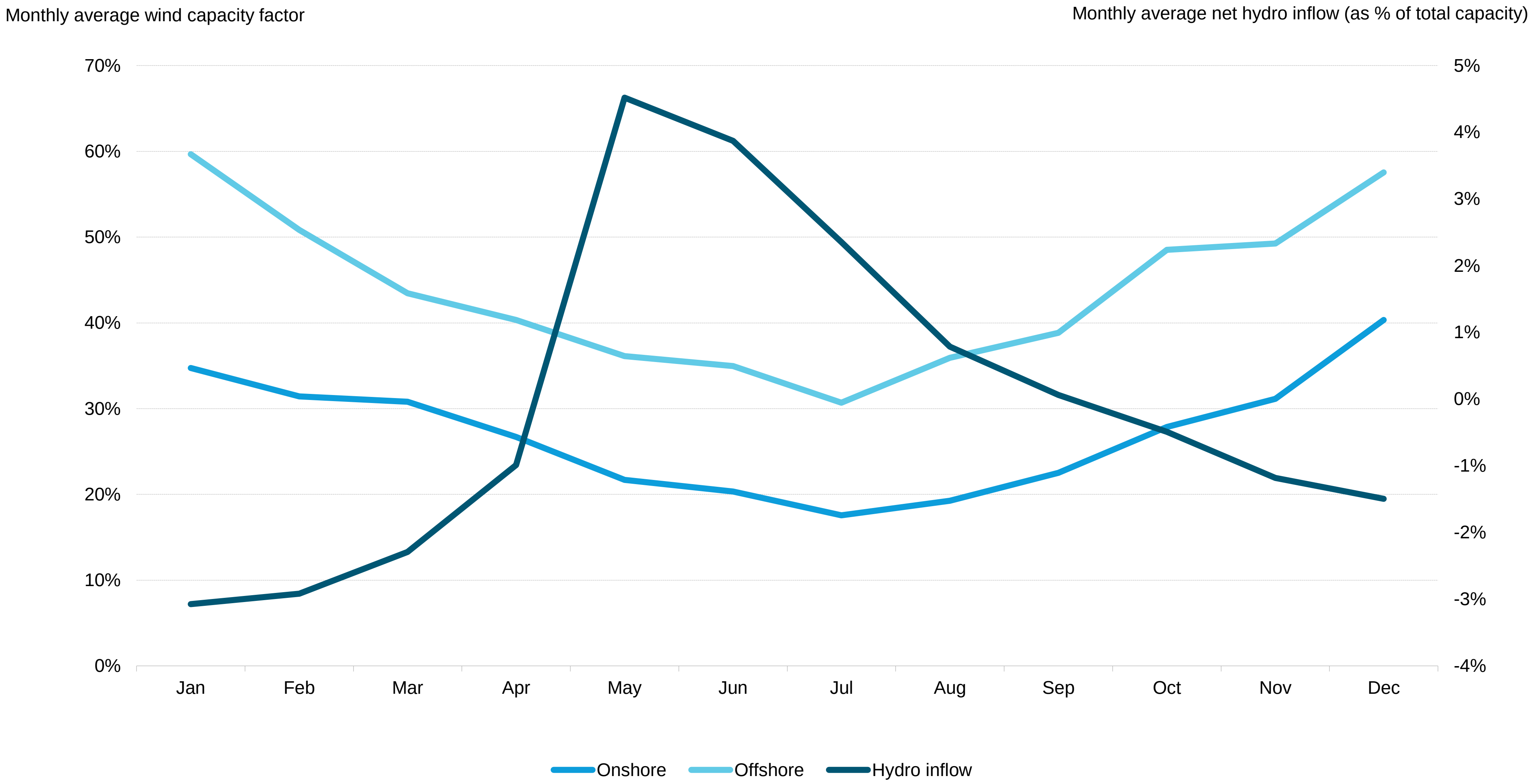
100%

- In this scenario, low-variable-renewables months see 26% of wind and solar energy. Unlike for the lowest wind/solar week, the demands placed on other generators are far from smooth. There is significant variation in wind and solar output taking place over the month – far more variation than that naturally provided by demand.

Note: a month is defined as a 730 hour period, not a calendar month.

Nordics: weekly, monthly and seasonal variability

Hydro and wind resources are complementary



Hydro and wind resources are complementary

Key trends

- The hydrological cycle in the Nordics is such that water inflow is at its lowest during winter, when water is mostly frozen, and at its highest during spring and summer, when snow melts.
- The opposite is true of wind power, which is higher over the winter when demand is high, and lower over the summer.
- The complementary nature of wind and hydro makes wind a good fit for the Nordic power system.

Notes

- Hydro levels increase from May to September, when net inflow is positive. These are the months when wind generation is lowest in the Nordics.
- The majority of wind generation, 60%, happens from October to March. This corresponds to the period when net hydro inflow is negative, meaning reservoir levels are decreasing.
- Hydro capacity levels peak in September (81% full), and are at their lowest in April (33% full).

Note: a month is defined as a 730 hour period, not a calendar month.

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About us

Bloomberg New Energy Finance authors

- Albert Cheung, Head of Analysis
- Jonas Rooze, Head of European Power Transition
- Andreas Gandolfo, Associate, European Power Transition
- Diego Marquina, Analyst, European Power Transition

With invaluable support from:

Eaton

- Cyrille Brisson, EMEA Marketing VP - Electrical Sector
- Jonathan Dinkeldein, Director EMEA Marketing Communications & Public Affairs
- Louis Shaffer, Distributed Energy Management Segment Manager EMEA

Renewable Energy Association

- Nina Skorupska, Chief Executive
- Frank Gordon, Policy Manager - Renewable Power, Energy Storage

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sales.bnef@bloomberg.net
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