THE NEED FOR CLEAN FLEXIBILITY IN EUROPE'S ELECTRICITY SYSTEM

A study on behalf of EUGINE & EUTurbines

05 JUNE 2023

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Executive Summary

Increasing electricity demand and more intermittent electricity generation pose significant challenges for Europe's security of electricity supply. Based on TYNDP 2022 data and historical weather years we have calculated hourly residual loads for all EU-27 countries for two different TYNDP scenarios (i.e. the Distributed Energy and the Global Ambition scenarios) in the years 2040 and 2050 and have analysed the **needs for flexibility solutions to bridge these residual loads**.

In particular, we conclude on the following points:

- Periods of high residual loads due to low in-feed from wind and PV which are lasting several days can be observed all over Europe - so-called "dunkelflaute" periods (energy droughts). In our study we present examples from the Western European countries of Belgium, the Netherlands, France and Germany as well as examples from Ireland and the Iberian peninsula.

- Even if we neglect existing transmission restrictions between all EU-27 countries ("copper plate" assumption for Europe) these dunkelflaute periods are no regional phenomena. While the expansion of interconnection capacity will play a crucial role in ensuring security of supply in Europe, it will not be enough. Additional flexibility measures like back up power, Demand Side Management or storage are needed to fully bridge supply gaps across Europe.

- These energy supply gaps in times of dunkelflaute periods can exceed 100 TWh in only a few weeks (compared to 3,012 TWh total generation from wind and PV over the full year). To put such a supply gap of 100 TWh into perspective: This corresponds to an amount that equals the storage capacity of around 1.4 billion Battery Electric Vehicles (BEV) or 12,500 large pumped storage hydro plants.

- Even when considering the flexibility potentials from short-term flexibility solutions such as demand side management (DSM), batteries and pumped hydro storage as well as from interconnector capacities, we show that **additional long-term flexibility solutions** such as power plants using climate-neutral gases are needed to bridge supply gaps in times of dunkelflaute.

- These longer term energy supply gaps can be observed regularly in a similar form. By varying underlying weather years we show that also in less stressful years (in terms of PV and wind energy feed-in over the full year), immense backup capacities are needed in certain hours to cope with peak residual loads. Looking at residual load duration curves for a whole year, we show that overall annual electricity generation from flexible generation capacity will be limited, i.e. the capacity will be mainly needed as backup ("insurance") to bridge dunkelflaute periods. Its overall annual power generation will be relatively small compared to annual RES-E infeed.

To foster investments into flexible power plants using climate-neutral gases and other flexibility options we suggest:

1. Recognising the need for all types of climate-neutral flexibility technologies

The European Commission’s emphasis on demand side flexibility and storage in the EMD reform proposal does not adequately address the need for more long-term flexible solutions. A clearer commitment from regulators to all forms of clean flexibility is needed – including technologies like flexible power plants using climate-neutral gases such as gas turbines or gas engines, which do not have to be fuelled with fossil gas – new modern turbines and gas engines can be operated with various green gases (hydrogen, biomethane, e-methane, etc).

2. Designing an assessment of flexibility needs that is technology neutral

The assessment of flexibility needs as proposed by the European Commission in Article 19c of the EMD reform proposal is a sensible measure to quantify gaps in the provision of flexibility and to increase transparency. However, deriving technology-specific and national objectives will not result in a cost-efficient provision of flexibility. Instead, flexibility needs to be thought of regionally and national authorities need to ensure that flexibility is fairly priced based on the type of flexibility provided (lead time, duration, region etc.).

3. Ensuring sufficient and fair income from reliable revenue streams

Investors in long-term flexibility solutions need clarity on remuneration for their investments. This requires fair compensation for electricity generation, capacity availability, and ancillary services. Marginal pricing with functioning price signals shall allow for sufficient rents to cover the marginal costs of production (plus additional rents to cover fixed costs in case an energy only market is installed). Capacity markets, in turn, can allow sufficient rents to cover investment and maintain capacity available for investment (while potentially lowering rents on the energy payments). Regarding capacity markets, the suggested additional criteria or features in the design of existing capacity mechanism to promote the participation of non-fossil flexibility shall not exclude clean, long-term flexibility solutions like flexible power plants using climate-neutral gases. Furthermore, the stable operation of electrical grids requires a variety of ancillary services such as short circuit power, synchronous condensers or voltage control. These can be intrinsically provided by flexible power plants using climate-neutral gases and shall be reflected in the market design (e.g. by ensuring fair remuneration for the service providers.)

4. Synchronising and accelerating the provision of climate-neutral fuels, infrastructures in electricity and hydrogen generation, and transmission

To achieve decarbonisation goals, it is crucial to increase the use of renewable fuels in the electricity mix. This requires streamlining the approval process for building the necessary generation capacities and transmission infrastructure for both vRES and hydrogen. Additionally, implementing a transparent certification system for renewable fuels and aligning sustainable financing obligations with carbon-neutral fuel availability will help ensure access to capital markets.

5. Rebuilding trust through a stable regulatory environment for investors

Proposals such as splitting short-term markets, questioning marginal pricing, and regulating prices for inframarginal technologies have created uncertainty for investors in electricity generation and flexibility technologies. Basic market principles shall not be questioned again during upcoming negotiations between EU institutions and Member States. Additionally, it is important to ensure that no policies are set in place that could devaluate flexible power plant assets, for instance an exclusion from flexibility schemes or capacity markets due to the unavailability of climate-neutral fuels.

Glossary

Battery Electric Vehicles (BEVs): Powered solely by an electric battery, with no engine. These vehicles are also considered as EVs, which is a broader term that encompasses all types of vehicles that use electricity as a power source, but not necessary solely by an electric battery.

Battery storage: The use of rechargeable batteries to store electrical energy. Battery storage systems are commonly used to address the intermittency and variability of renewable energy sources, such as solar and wind power by storing excess energy during periods of low demand or high generation and releasing it during periods of high demand or low generation.

Climate neutral gas: a gas or fuel which produces no net-greenhouse gas emissions or carbon footprint. This includes, inter alia, renewable gases, hydrogen and its derivates.

Demand side management: (DSM) Approach to optimise the overall energy system by encouraging consumers to modify their level and pattern of electricity usage. It helps in balancing electricity supply and demand more efficiently, reducing the need for additional power generation capacity, and improving grid reliability.

Dunkelflaute: Situations in which there is a combination of low or no sunlight and low or no wind, leading to reduced energy production from solar PV and wind turbines for consecutive days or even weeks. Also known as "dark doldrums", "anticyclonic gloom" or "energy droughts".

Flexible power plants using climate-neutral gases: Dispatchable power generation systems that use gaseous fuels such as renewable gas or hydrogen or abated natural gas to produce electricity and, optionally, heat (when running as cogeneration or CHP plants).

Gas turbines or gas engines: Key components of a flexible power plant that converts fuels such as renewable gas or hydrogen into mechanical energy, which is then used to generate electricity.

Heat pump: A device that transfers heat from one location to another, typically for the purpose of heating or cooling spaces.

Interconnectors: Infrastructure systems that link different regional or national electrical grids together. They are high-voltage transmission lines or cables that enable the exchange of electricity between interconnected power systems.

Intermittent generation: Production of electricity from renewable energy sources that are inherently variable and unpredictable in their power output. It primarily includes energy generated from sources such as solar and wind, which are dependent on weather conditions.

Flexibility solutions: Measures and technologies that enable the adjustment of electricity supply or demand in response to changing conditions in demand, in intermittent generation and/or disruptions to the energy system. Flexibility solutions can be used to help balancing the system for shorter gaps, e.g. hourly and daily gaps or for longer gaps, e.g. weekly and monthly.

Full load hours (FLH): It represents the number of hours a power plant operates at full power output, relative to the total number of hours in that time period.

Residual load: The amount of electricity demand that remains after accounting for generated electricity. It is the difference between electricity demand and electricity produced.

Security of supply: Reliability and resilience of the energy system to provide sufficient energy supply to meet the demand of consumers.

TYNDP: Ten Year Network Development Plan

Value of lost load: An estimation in euro/MWh, of the maximum electricity price that customers are willing to pay to avoid an outage. It is the monetary value or economic cost associated with power outages or interruptions.

vRES : Variable renewable energy source

Increasing electricity demand and more intermittent generation: Europe's security of supply can be at risk

In 2021, the EU ambitiously introduced the so-called "Fit-for-55 legislation package" with several climate proposals, aiming to reduce greenhouse gas emissions by 55% by 2030 compared to 1990 levels and achieving climate neutrality by 2050. The ramping up of renewable electricity into the electricity system plays a crucial role in achieving these goals.

In order to reach the energy and climate targets defined in the European Climate Law, the deployment of renewables will need to triple by 2030.[1] Estimates for 2040 and 2050 can be taken from ENTSOG's and ENTSO-e's most recent Ten-Year Network Development Plan (TYNDP) 2022[2], which entails two different scenarios: the Distributed Energy and the Global Ambition scenario.

While both scenarios assume a fully decarbonised EU by 2050, the approach to achieving this goal is different. The Distributed Energy scenario assumes a higher degree of European autonomy, with a focus on renewable and decentralised electricity generation within the EU. In the Global Ambition scenario, the EU's dependency on energy imports is higher due to a global economy with centralised low-carbon and renewable energy options.

Expected capacities from renewables are planned to increase by at least 154% by 2030 and quintuple by 2050 from today's values, according to the Global Ambition scenario (Figure 1). In the Distributed Energy scenario, the expected increase in renewable capacity is about 700% higher by 2050 than in 2023. In particular, it forecasts that 76% of EU's power capacity will come from solar and wind in 2050, making generation largely dependent on weather conditions.

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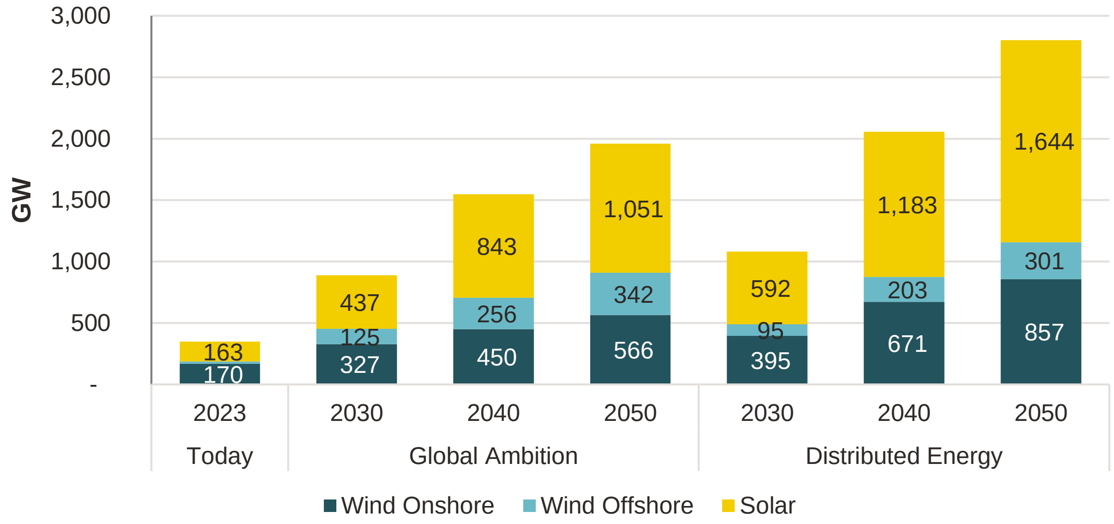
[1] https://climate.ec.europa.eu/eu-action/european-green-deal/european-climate-law_en

[2] https://2022.entsos-tyndp-scenarios.eu/download/

Figure 1 Wind and PV capacities for EU-27 according to TYNDP 2022 scenarios



Source: TYNDP 2022, RES capacities under scenarios Global Ambition and Distributed Energy. Today's values were taken from ENTSO-E Transparency Platform in "Installed Capacity per Production Type" data page

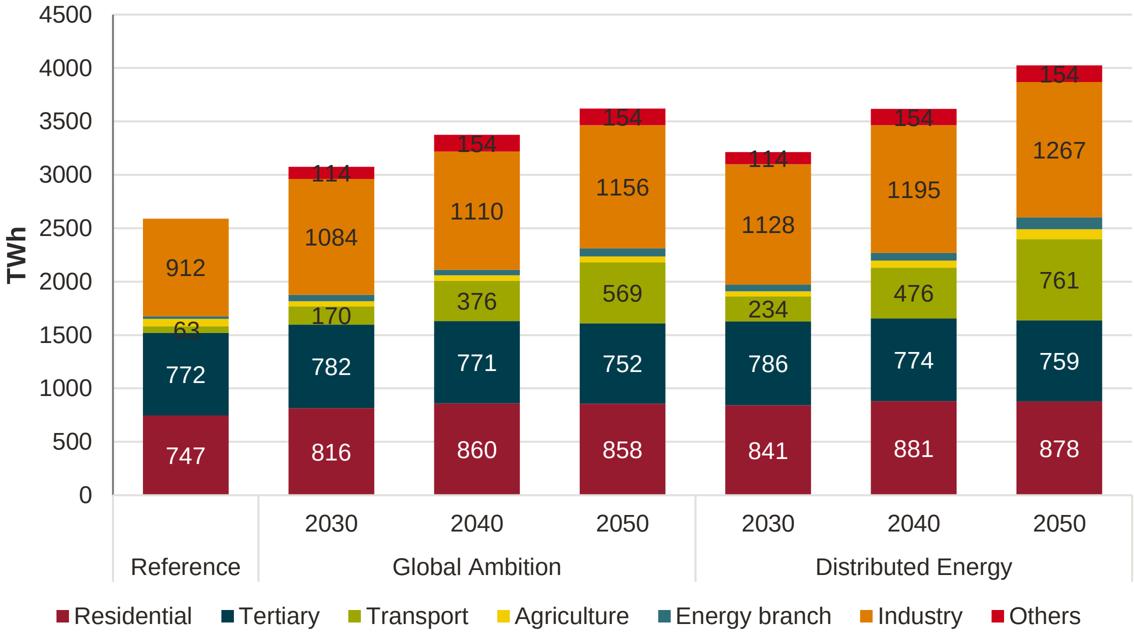
While a renewables-based energy system is the way to meet climate targets, it also brings in new challenges. As renewable energy is inherently intermittent by nature, there is no guarantee that sufficient electricity will be generated at all times needed. Furthermore, even when (scheduled) generation exactly matches demand, a variety of so-called "ancillary services" is required to keep the grid stable (such short circuit power, frequency control, voltage control). Today, these are in most grids implicitly provided by the synchronous generators in classical thermal power plants.

At the same time, the decarbonisation will lead to an accelerated electrification of sectors such as mobility, heating and industry. This will drastically increase the demand for electricity in the coming years. Figure 2 shows an increase in electricity demand of 55% under the TYNDP's Distributed Energy scenario and of 39% in the Global Ambition scenario in 2050 compared to today. Electricity demand differs in both scenarios, given that a higher reliance on energy imports in the Global Ambition scenario lead to a lower degree of electrification (and a higher share of hydrogen in the final energy demand) compared to the Distributed Energy scenario. It also shows major growth in electricity demand coming from the transport sector.

While the transport sector in the reference year only demands 63 TWh of electricity, it is expected that, in 2030, this will be 4 times higher under the Distributed Energy scenario. Moreover, electricity demand will become more seasonal due to the electrification of heating.

For instance, around 60 million heat pumps are expected to be installed by 2030 to meet the EU's targets.[3]

Figure 2 Final electricity demand for EU-27 per sector according to TYNDP 2022 scenarios



Source: Based on Figure 8 of TYNDP 2022 Report

Note: For residential and tertiary sectors, values are based on 2018. For the other sectors, values are based on 2015. Energy branch is the electricity required to produce itself (energy)

Higher electricity demand combined with more variable generation will challenge Europe's security of supply. Policy makers need to ensure that the future energy system is able to meet demand at all times. Low levels of security of supply can be costly for society, both for individuals and for the industry. Even the perceived risk of low security of supply can influence investment decisions by industrial players. An electricity system must be robust enough to cope with quite challenging situations (e.g. a very cold, rather than just a typical cold, winter working day) – it cannot be built to cope with average situations. Our analysis shows that significant energy shortages will occur on a fairly regular basis, not necessarily always resulting in a 100 TWh gap in a 3-week period, however, will have significant gaps (see Figure 8 for details).

In this short report, using data from the latest TYNDP 2022, we show that Europe will experience prolonged periods of low wind and PV input over several consecutive days, and

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[3] https://www.ehpa.org/2022/06/12/ehpa_news/repowereu-heat-pump-strategy-required-to-help-sector-deliver/ (Published on 12th June 2022, last accessed on 8th May 2023)

that all types of flexibility instruments will be needed on a large scale to bridge the expected supply gaps. In addition to increasing interconnector capacity, this includes short-term flexibility measures such as demand-side response and storage that can bridge supply gaps for several consecutive hours, but also molecule-based flexible firm generation using climate-neutral gases that can deliver when the potential of DSM has been exploited and battery storage has been exhausted. We conclude with five policy recommendations on how to encourage investments in flexible and firm electricity generation in an investment environment that has increasingly become less stable and reliable.

Situations with low feed-in from wind and PV occur all over Europe

Wind and solar power will be the backbone of the future power supply in Europe. However, the output of wind and solar power, as well as the electricity consumption, can fluctuate significantly throughout the day. Not only intraday fluctuations are a concern but also prolonged unfavourable weather conditions or seasonal fluctuations in feed-in from wind and PV.

Dunkelflaute periods are becoming a major concern for the economy. These meteorological events are characterised by low wind and low sun in-feed that could last from only a few hours to consecutive days or even weeks. Particularly in winter, weather conditions can occur where there is little sunshine and little wind, resulting in low feed-in from wind and solar. If these events coincide with periods of low temperatures, where demand is higher due to increased electrification of heating, the security of supply is significantly at risk.

Forecasting prolonged dunkelflaute periods is a critical task for market participants, regulators and policy makers in order to enable an adequate deployment of short- and long-term flexibility capacities. The literature shows that dunkelflaute events occur regularly in Europe. Periods of more than 24 hours of low vRES infeed occur every year, in particular between November and January[4]. Also longer, more extreme periods of several weeks with low PV and wind input are quite common. In Germany, for example, energy shortages of more than two weeks occurred every second year between 2006 and 2016.[5]

Based on the most recent TYNDP 2022 data (including projected installed capacities) and different historical climate years, we have modelled the hourly electricity generation from wind, solar, nuclear and run-of-river[6], and demand for all EU-27 Member States for the years 2040 and 2050 under both the Global Ambition and Distributed Energy scenarios. More details on the modelling approach can be found in the technical Annex A .

As mentioned above, we have considered both scenarios in our analysis, but recent efforts by policy makers across Europe to reduce energy import dependency following the Russian attack on Ukraine suggest that the Distributed Energy scenario can be considered the most likely from today's perspective.

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[4] Li, B., Basu, S., Watson, S. J., & Russchenberg, H. W. J. (2021). A Brief Climatology of Dunkelflaute Events over and Surrounding the North and Baltic Sea Areas.

[5] Energy Brainpool (2017): Kalte Dunkelflaute - Robustheit des Stromsystems bei Extremwetter

[6] We also include generation from other renewables which are biofuels, marine, geothermal, waste, and any other small renewable technologies and other non-renewable which includes mainly CHP that is used in district heating & industry.

Our modelling shows that the occurrence of dunkelflaute events results in high residual loads[7] over a prolonged period of several days, and that they occur regularly across Europe – irrespective of the year and scenario chosen. In the following we present by way of example some identified periods for

- the Western EU Member States Belgium, the Netherlands, France and Germany, representing countries with high electricity demand but mixed weather conditions for wind and PV,
- Spain and Portugal for countries with particularly high solar irradiation and good wind conditions, and
- Ireland for countries with particularly good wind conditions but limited possibilities to exchange electricity.

Figure 3 shows the demand and the different forms of electricity generation for clustered Western EU countries as projected in Distributed Energy scenario of the TYNDP 2022 for the years 2040 and 2050. The first graph of Figure 3 shows projected capacities and demand for the year 2040 assuming the weather conditions from December 1995, which has been among the more stressful weather years according to TYNDP 2022.[8] As it can be observed, there are several consecutive days when these countries together experience significant supply gaps. In particular high residual loads can be observed between 16 and 23 December.

The grey area between the red demand line and the production from RES-E, hydro power and nuclear is the supply gap which has to be dealt with by the flexibility options like storage, DSM, power exchange and flexible dispatchable generation (e.g., flexible power plants using climate-neutral gases[9]). Similarly, taking capacities and hourly power demand projected for the year 2050 and using RES-E production profiles of weather conditions as observed in January 2010, a large supply gap lasting several days can be observed in January.

In summary, the remaining positive residual demand over the almost 3-week period of the dunkelflaute means that the system would have to balance a supply gap of around 48 TWh in the first example and a total gap of almost 57 TWh in the second example - both in a period of less than a month. This gap roughly compares to today's entire yearly electricity consumption of countries such as Portugal or Switzerland.[10] The peak capacity required to bridge this gap is 196 GW in 2040 and 195 GW in 2050. Reduced by 74 GW of projected DSM

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[7] Residual loads refer to the amount of electricity demand that remains after accounting for certain generated electricity. In our model residuals loads is demand minus generated electricity from wind, solar, nuclear, run-of-river, other renewables and other non-renewable production. More details can be found in the technical annex.

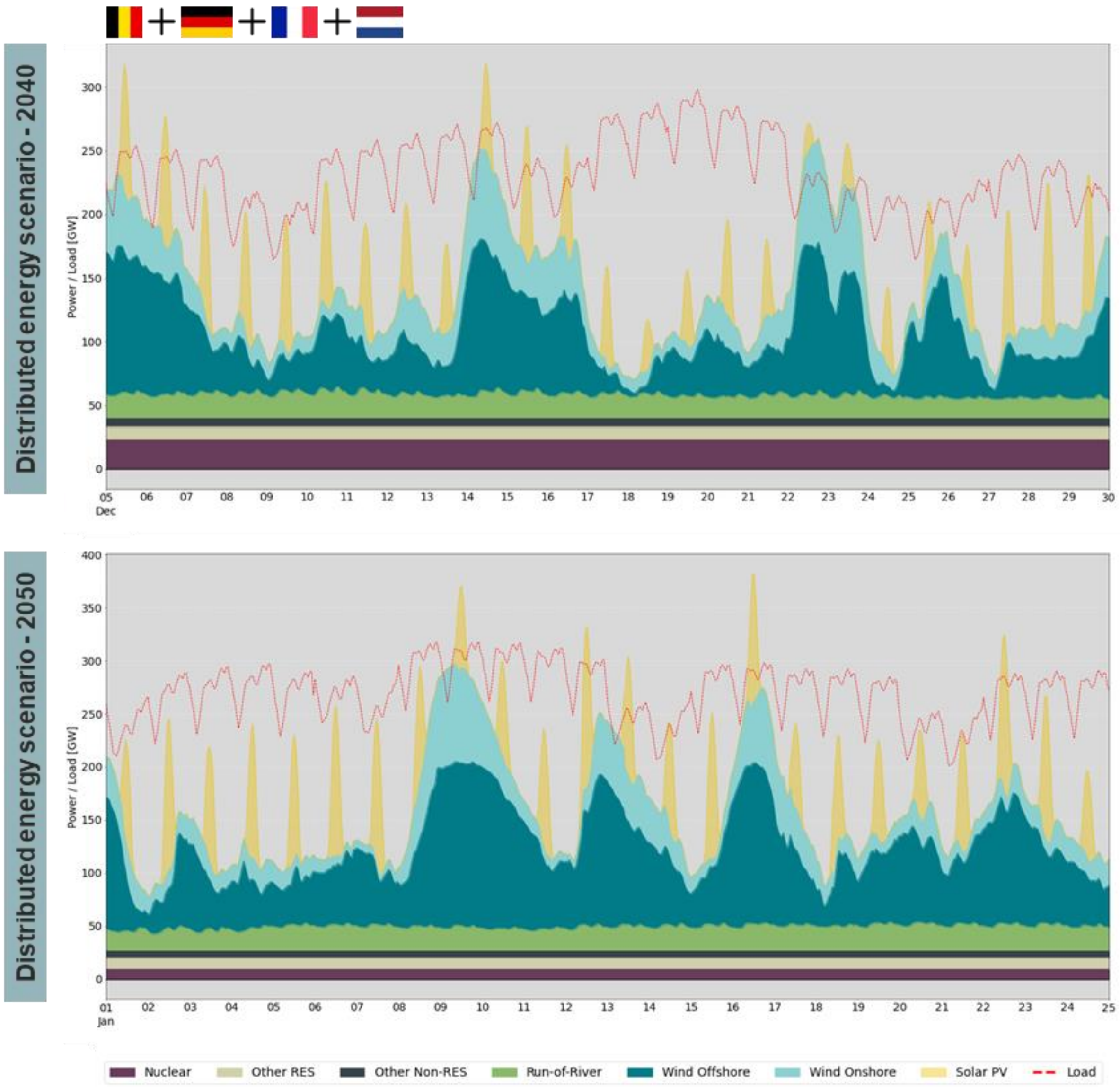
[8] TYND 2022: Scenario Building Guidelines, p. 43

[9] Plants which cover the gap today and which are fired with lignite, coal or fossil gas or oil will not be used anymore by 2050.

[10] World Data Info – Portugal 48.2 TWh https://www.worlddata.info/europe/portugal/energy-consumption.php and Switzerland 56.4 TWh https://www.worlddata.info/europe/switzerland/energy-consumption.php

capacity, this would still leave 122 GW to be bridged by other flexibility options such as storage or flexible generation.

Figure 3 Electricity generation and demand during a dunkelflaute period – examples from Western Europe for 2040 and 2050



Source: *Frontier Economics based on TYNDP 2022 data*

Note: *Production profiles for RES for the first figure are based on Dec 1995 while for the second are based on Jan 2010 which has been similarly stressful in terms of weather conditions as 1995 according to TYND 2022*

Figure 4 shows a similar case for Iberia under the Global Ambition scenario in the year 2040 using projected RES-E production profiles based on the weather conditions from January 2009 but with a high installed PV and wind capacity, as projected by the TYNDP for 2040.

The Iberian peninsula is a favoured region for renewable electricity generation given its excellent weather conditions for wind and PV. However, significant supply gaps can still be observed during the winter and to an extent that it can challenge the ability to ensure the security of supply with additional backup power plants in addition to storage and DSM.

During this two-week period for the Iberian Peninsula, positive residual load sums up to a total gap of 6.5 TWh in Portugal and Spain.[11] Again, this will need to be covered by storage, DSM, power exchanges and back-up generation (guaranteed and dispatchable). DSM alone could only reduce the residual load by 1.6 GW, but the region peaks at 49.5 GW during this period. Assuming sufficient excess electricity to be shifted via batteries, the assumed installed battery capacity of 25.5 GW would need to be loaded and unloaded more than 250 times, or 18 times per day, which is highly unrealistic given that typical residential battery storage is based on 200 to 250 charge cycles per year over a 15 to 25 year lifetime.

Similarly, Figure 5 displays an example of a dunkelflaute period of nearly 20 consecutive days in June for Ireland under the Distributed Energy scenario in 2040. Despite the typically strong and high wind generation on the island, 1.2 TWh of electricity generation is missing to meet local electricity demand during this summer period between 8 June and 30 June based on weather conditions from 1987. Taking into account DSM and battery storage, residual loads could be reduced by 1.6 GW, which it is not sufficient to fill the gap during this period, particularly during the peak hour at 5 GW.

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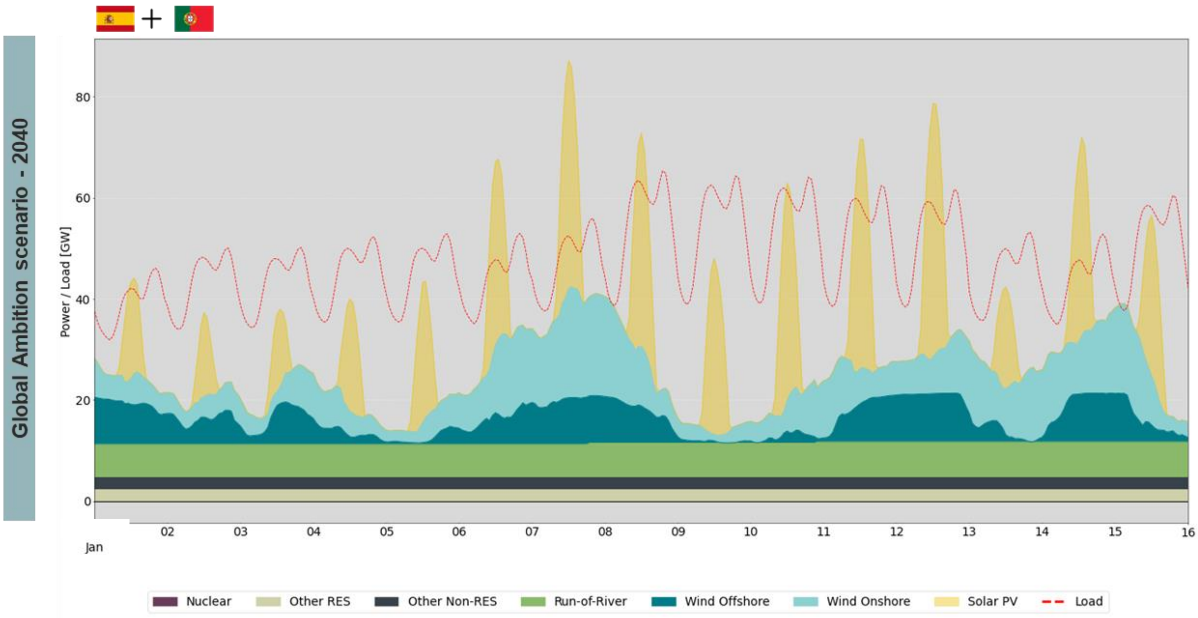
[11] Results under the Distributed Energy scenario are even larger and result in a gap of 7.8 TWh in the respective period assuming the same weather conditions.

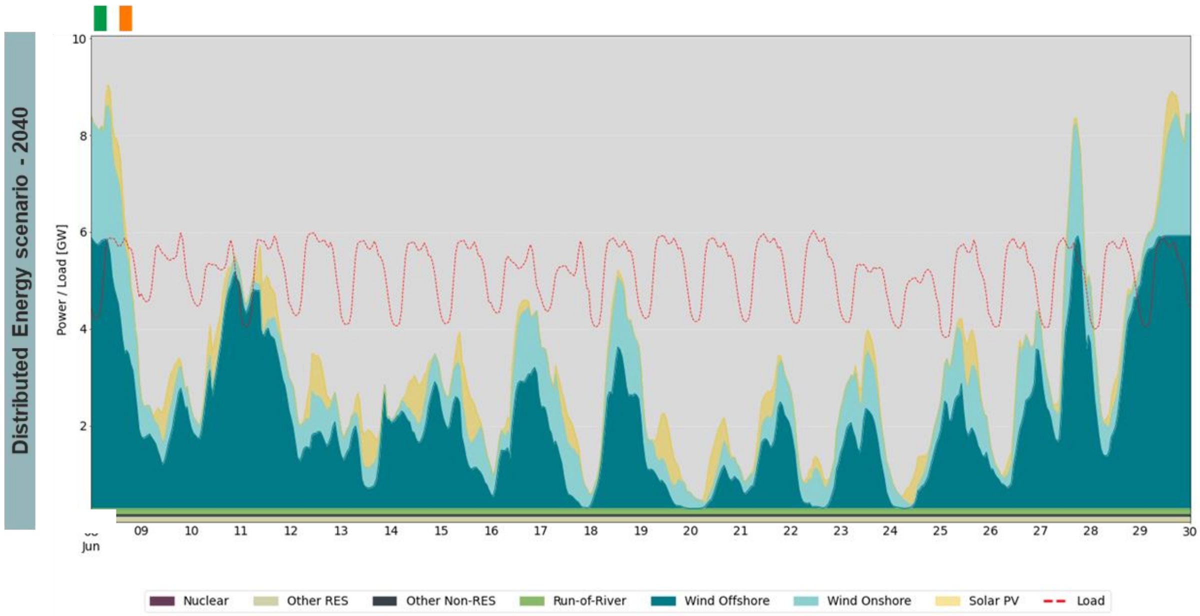
Figure 4 Electricity generation and demand during a dunkelflaute period – an example from the Iberian Peninsula for 2040



Source: *Frontier Economics based on TYNDP 2022 data*

Note: *Production profiles for RES are based on January 2009 which has been another rather stressful year in terms of weather conditions according to TYND 2022*

Figure 5 Electricity generation and demand during a dunkelflaute period – an example from Ireland for 2040



Source: *Frontier Economics based on TYNDP 2022 data*

Note: *Production profiles for RES are based on June 1987 which has been another rather stressful year in terms of weather conditions according to TYND 2022.*

Conclusion

As a result, our modelling exercise has shown that irrespective of which scenario and year ahead we have looked at, we have consistently identified longer supply gaps across Europe lasting several consecutive days or even weeks. It is impossible to project when exactly and where exactly these dunkelflaute events will occur – it is, however, clear that many regions in Europe will be affected. There is no reason to believe that the occurrences of dunkelflaute events will cease in the future. On the contrary, extreme weather events are expected to become more frequent due to human-caused climate change.[12] The local distribution of RES-E across Europe as well as stronger networks will help to fill these gaps – but this will not solve the issue (in our example we have assumed a "copper plate" with perfect power exchange for the region Belgium, Netherlands, Germany and France – and still the supply gap occurs as described above[13]). Constantly filling those gaps will become a central challenge for the future fully decarbonised European electricity system.

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[12] https://www.carbonbrief.org/mapped-how-climate-change-affects-extreme-weather-around-the-world/

[13] We will look into the details of the effect of power exchange in the next section.

Investments in the electricity grid alone will not be sufficient to fully close longer supply gaps: The copper plate example

An important instrument to cope with situations of dunkelflaute periods is to increase the transmission capacity of interconnectors, so that regions with better weather conditions can meet demand in other regions in distress. In particular, the EU's single energy market has brought several economic benefits for consumers and operators. The ability of countries to exchange electricity with each other not only has helped to secure electricity but also has reduced energy bills. For instance, thanks to the recent addition of Alegro interconnector (1 GW) finished in 2020[14], in times of particularly good weather conditions for wind and PV in Germany, Belgian households are also able to benefit. Hence, it is extremely important to maintain investments in the grid by building new transmission lines, upgrading existing infrastructure, and implementing new technologies to optimise the use of the existing network in order to attain an efficient and well-functioning single market.

European countries do not only vary in their generation mix and weather patterns, but they also have different demand profiles. Generally, a country experiencing high residual loads could simply import more electricity from a neighbouring country via interconnectors. However, the presence of dunkelflaute events is not always an isolated episode. These events can occur simultaneously in different regions.

One way of demonstrating this is the so-called "copper-plate" approach, which refers to a theoretical model of electricity transmission that assumes a perfectly efficient transmission grid. Under this assumption, electricity is transmitted between generators and consumers in the most direct and efficient way possible, without any congestion issues or transmission losses. In other words: there are no barriers to transmitting electricity from, say, Portugal to Finland. Already the Western Europe examples (Figure 3) assume no transmission barriers between the countries included and is thus a very conservative approach to identifying periods of high residual loads.

By assuming a copper plate for all EU-27 we can go even further. Our analysis shows that, even under perfect transmission conditions, there are periods where electricity is scarce and where it will be difficult to cover demand all over Europe.

Figure 6 illustrates an example of residual loads for the whole EU-27 in the period from January 1st to January 26th under the Distributed Energy scenario for 2050. The line represents the residual load per hour, i.e. the difference between the hourly demand and the electricity generation from wind, PV, nuclear, run-of-river and other smaller firm capacities (see the technical annex for more details). Hours where the residual load is above 0 represent hours with supply gaps where flexibility options are needed to meet demand. Only during very few

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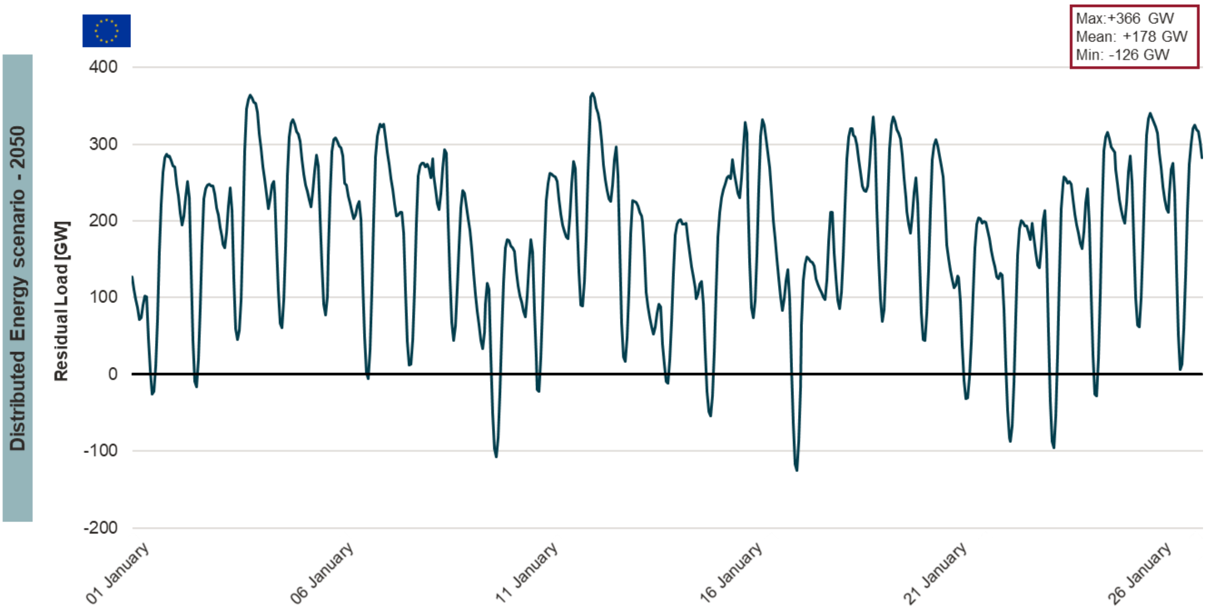
[14] https://www.amprion.net/Press/Press-Detail-Page_37505.html (Published in 25th November 2021, last accessed 8th May 2023)

hours in that given period, sufficient electricity is generated all over the EU-27. In these hours, the residual loads become negative.

The example in Figure 6 shows that, even in a scenario where there is perfect distribution among countries, the presence of a prolonged dunkelflaute event still means that a significant share of demand needs to be covered during such extreme winter weeks via other flexibility options. We will further elaborate on this example in the following chapter.

Figure 6 Example for total residual loads for EU-27 countries during a low in-feed period in January 2050 (copper plate assumption)



Source: Frontier Economics based on TYNDP 2022 data

Note: Production profiles for RES are based on weather conditions as of January 2010 which has been another rather stressful year in terms of weather conditions according to TYND 2022.

Conclusion

Further market integration via expansion of interconnectors will, without a doubt, play a crucial role in meeting security of supply in Europe. However, it will not be sufficient and will need to be complemented by other flexibility solutions. Therefore, ensuring that the appropriate backup technologies are in place to support electricity markets when renewable generation is low will be key to maintain security of supply and consumer protection for the EU.

The contribution from short-term flexibility solutions to bridge longer supply gaps will be limited

Flexibility solutions will be key components for the functioning of the future decarbonised energy markets. This includes short-term solutions such as stationary batteries, pumped hydro storages or DSM, which will close some of the gaps and shift energy to hours when electricity is scarce, in particular, intra-daily or day-to-day. However, the contribution impact will need limited when bridging longer supply gaps.

Returning to the copper plate example for the EU-27 (Figure 6) can help to understand the extent of the back-up service that short-term flexibility technologies can contribute in these situations.

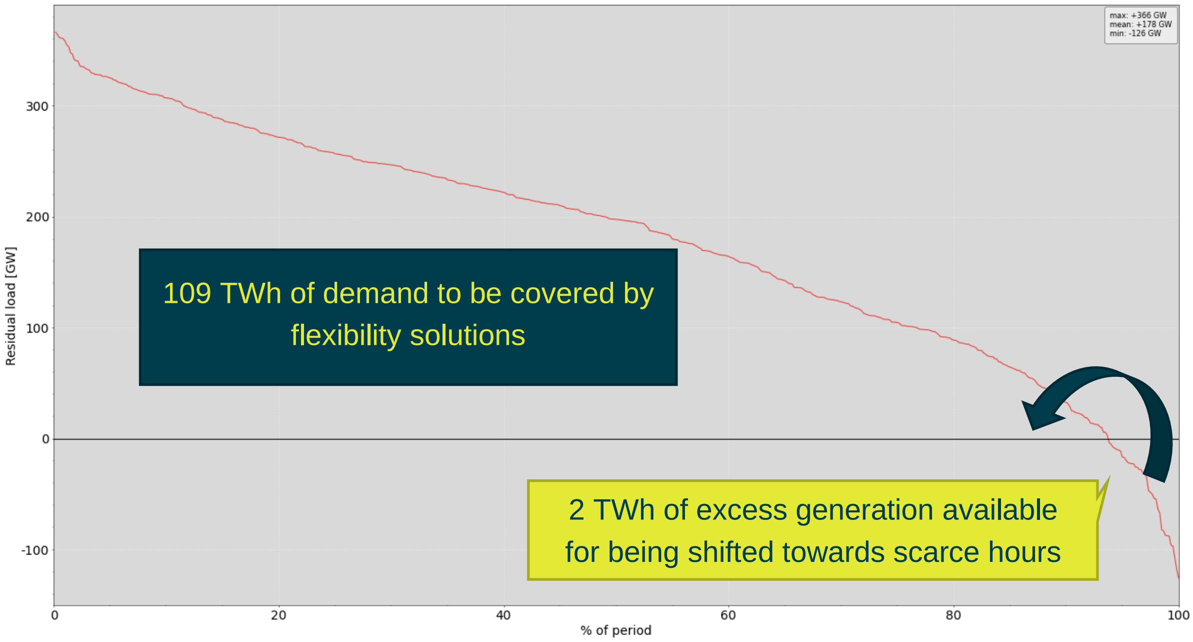
Figure 7 shows the residual load duration curve for the dunkelflaute period or, in other words, the supply gap after (assumed) perfect transmission of electricity all over EU-27. The curve is created by sorting the residual load values for each hour in the three-week period in descending order of magnitude. The vertical axis of the curve represents the residual load in gigawatts (GW), while the horizontal axis represents the percentage of time that the residual load is at or below a given value.

The total amount of positive residual loads – represented by the area above zero and below the residual duration curve, sums up to 109 TWh, whereas the area with negative residual loads (surplus energy supply) only sums up to roughly 2 TWh in that period. In the most stressful hour, a maximum residual load of 366 GW would need to be bridged. Even if it is assumed that the 2 TWh of surplus energy can be perfectly shifted to hours of scarcity by stationary batteries, there is still a gap of more than 107 TWh for this (roughly) 3-week period.

The estimated DSM potential of 35 GW by the TYNDP 2022 will play a part in reducing the peak residual load, which amounts to a maximum of 366 GW in the given example period. The same applies to the estimated 59 GW of installed pumped storage. However, most of the remaining load will have to be met by flexibility solutions that can bridge longer supply gaps, such as flexible power plants using climate-neutral gases.

Looking at this stylised example, which assumes perfect transmission across Europe and is therefore a conservative approach, peak residual loads of over 300 GW seem very likely, even after taking into account the potential of DSM, batteries and pumped storage. This is discussed further in the following chapter.

Figure 7 Residual load duration curve for EU-27 in January 2050



109 TWh of demand to be covered by flexibility solutions

2 TWh of excess generation available for being shifted towards scarce hours

Source: *Frontier Economics based on TYNDP 2022 data*

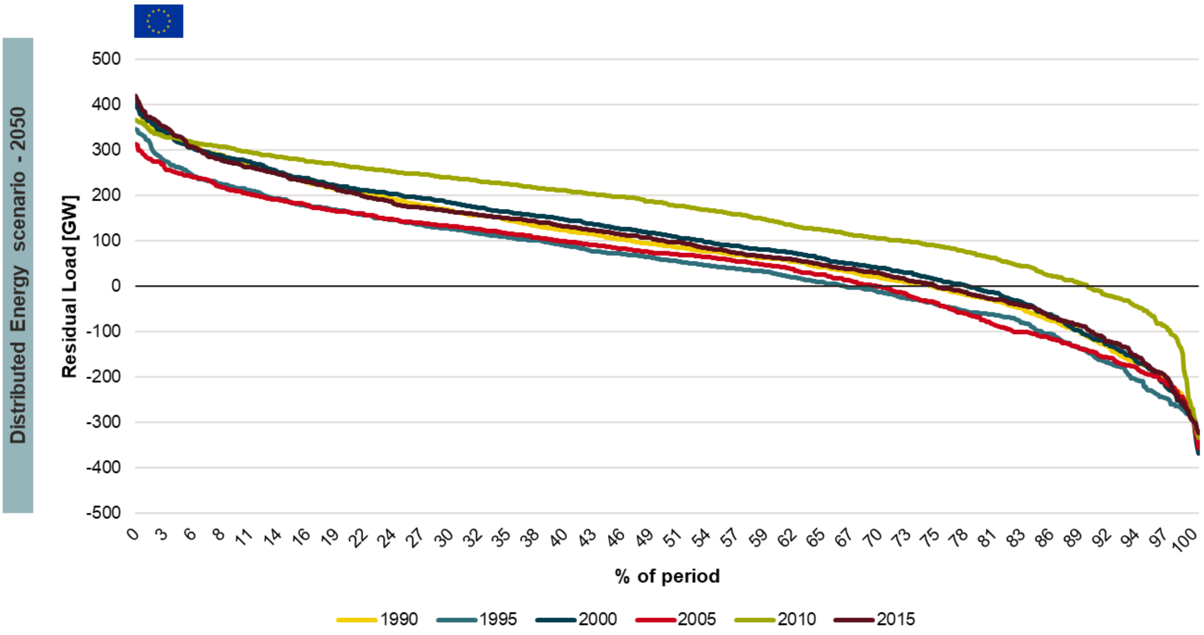
Note: *Production profiles for RES are based on weather conditions as of January 2010 which has been among the rather stressful years in terms of weather conditions according to TYND 2022.*

The EU-27 copper-plate example shown in Figure 6 and Figure 7 assumes weather patterns as occurred in 2010, which according to TYNDP 2022 was one of the most severe weather years since 1986. However, even when using different weather years (e.g. every fifth year since 1990), large residual loads are regularly observed in the winter months.

Figure 8 shows the residual load curves for six different weather years for the Distributed Energy Scenario for the month of January in the year 2050. The green line represents the weather year 2010, as shown in the previous figures. 2010 is clearly one of the most stressful years, with a residual load duration curve that lies above the other ones in the corresponding period (i.e. shows higher residual loads in more hours).

However, even if we assume less stressful weather conditions, there are still large residual loads. The peak residual load (in GW), which is the residual load at the very left of each curve, is, in some cases, even higher than in the 2010 example and can exceed 400 GW. This means that even though the total amount of generation (in TWh) needed to bridge the overall supply gap varies in the different examples, the total capacity (in GW) needed in certain hours is immense in all examples (detailed results can also be seen in the technical annex). Backup capacity to bridge these peak load hours is urgently needed in every single example.

Figure 8 Residual load duration curves for EU-27 in January 2050 assuming different historical weather conditions from different climate years



Source: Frontier Economics based on TYNDP 2022 data

Conclusion

The stylised copper plate example for the EU-27 is a very conservative approach to estimating residual loads, as it assumes no transmission constraints between Member States. Nevertheless, the residual load duration curves for the month of January for different weather years for the EU-27 under the Distributed Energy scenario for 2050 have shown that in the most stressful weather years, such as 2010, very little excess electricity will be available to cover this long-term gap. This shows the importance of flexible, dispatchable generation capacity in those dunkelflaute periods.

In order to avoid costly electricity shortages, an electricity system must be able to provide sufficient generation also during the most extreme weather conditions. It is important to plan for flexible capacity that can cover the more extreme weather patterns, not just the average ones. This is why our analysis focuses on more stressful weather years and on TYNDP's Distributed Energy scenario, which assumes higher electricity demand than the Global Ambition scenario.

However, even taking into account less stressful weather years than for example 2010 and individual hours with excess electricity (i.e. negative residual loads), a significant supply gap can still be expected on a regular basis. In addition to the energy supply gap (TWh), it is important to note that several hours with very high positive residual loads of more than 400

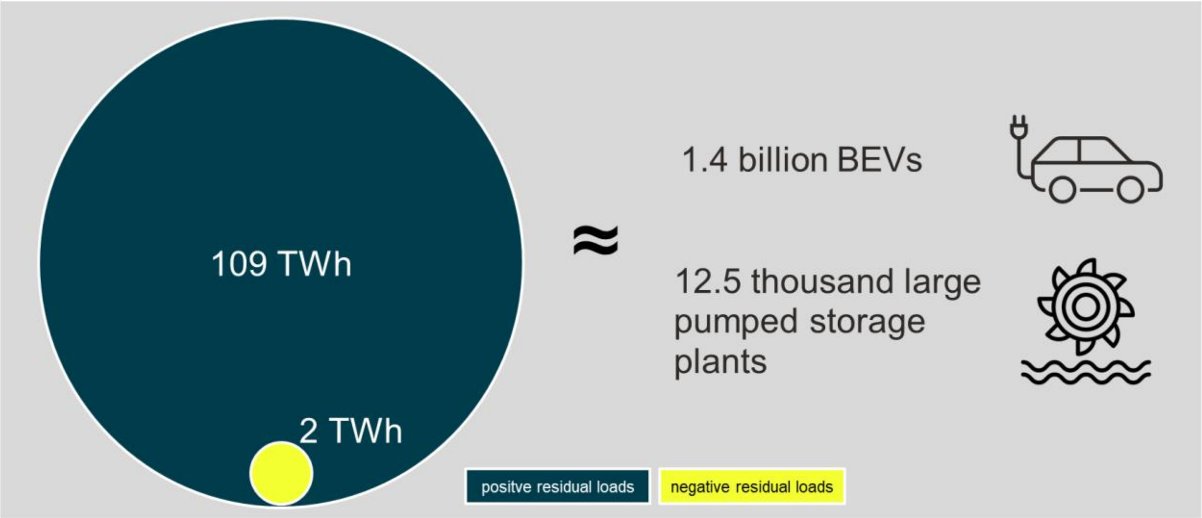
GW can be expected, implying that significant amounts of flexible generation capacity will be needed to maintain security of supply. The following chapter puts these figures into perspective.

1.4 billion BEVs to close the supply gap – or the urgent need for flexible backup generation capacity

In Figure 7, we have shown that for the dunkelflaute presented in 2050, and assuming 2010 weather conditions, the total positive residual load is 109 TWh, while the negative load is only 2 TWh over this three-week winter period. In other words, in our stylised copper-plate example, the cumulative supply gap over the given period is 55 times larger than the negative residual load.

Fully filling this three-week supply gap by means of electricity storage would require around 1.4 billion Battery Electric Vehicles (BEV)[15] or 12,500 large pumped-hydro storage plants[16]. If we compare this to the 250 million or so passenger cars in operation today in the EU-27 (and which are mostly ICE anyway), the challenge of bridging longer supply gaps becomes clear.

Figure 9 The EU-27 copper plate example in practice



Source: Frontier Economics based on TYNDP 2022 data
Note: Period 01.01.2050-25.01.2050 Distributed Energy Scenario

Demand-side management (DSM) technologies will be another option to bridge supply gaps, in addition to interconnectors, batteries and pumped storage. DSM programmes and strategies can be particularly effective in balancing the grid during times of high demand, such as hot summer evenings when air conditioning use is high, but solar PV generation is low. By

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[15] EV database, Tesla Model 3 Long Range - Capacity: 75 kWh, Base power: 75-125 kW, Peak power: 175 kW

[16] Vattenfall, Goldisthal Pumped-storage Power Plant - Storage capacity: 8.5 GWh, Power capacity: 1060 MW

reducing demand during these periods, DSM can help prevent blackouts, brownouts, and other grid disruptions.

However, there are limits to the extent to which DSM can bridge supply gaps. First, the estimated overall load reduction for the EU-27 under the TYNDP 2022 Distributed Energy scenario only amounts to 35 GW, which is less than 10% of the load to be covered in the hours with the highest residual load (i.e. 366 GW in our example in Figure 7). Second, in times of prolonged duration of high demand but low generation, such as during cold dunkelflaute periods, even the most effective DSM programmes will not be enough to meet the demand for electricity. In particular, heating and cooling in combination with heat storage and isolation of buildings will be interesting DSM options to bridge shorter gaps.

However, the longer demand side measures are used, the more costly they will become. For instance, in some industry processes, a refrigerator or a freezer can shut down for hours without any harm and at low cost but, after a certain number of hours, the heated or cooled goods will cool down or warm up and costs for DSM can escalate. The values of lost load, which are the amount of money that consumers are willing to pay to avoid or compensate for the negative consequences of an electricity supply disruption, are significant. A recent study for the Netherlands has determined these sectoral costs can add up to 106,000 €/MWh (Figure 10). For longer term supply gaps, additional supply-side measures in form of flexible backup generation capacities are necessary to ensure the reliability of our electricity system.

Examples from the United States provide warning use cases where insufficient investment in generation capacity led to severe electricity crises. In the early 2000s, California faced electricity shortages due to supply and demand imbalances, resulting in rolling blackouts. The total cost of the crisis amounted to around $40 billion to $45 billion or around 3.5 percent of the yearly total economic output of California in only two years.[17] In the winter of 2021 in Texas, during a cold spell, about 40% of the generation fleet failed, forcing the TSO (ERCOT) to leave millions of customers without power for several days. Estimations indicate that the freeze and outage may have cost the Texas economy $80 billion–$130 billion in direct and indirect economic loss. The value of lost load has been estimated at $4.3 billion.[18]

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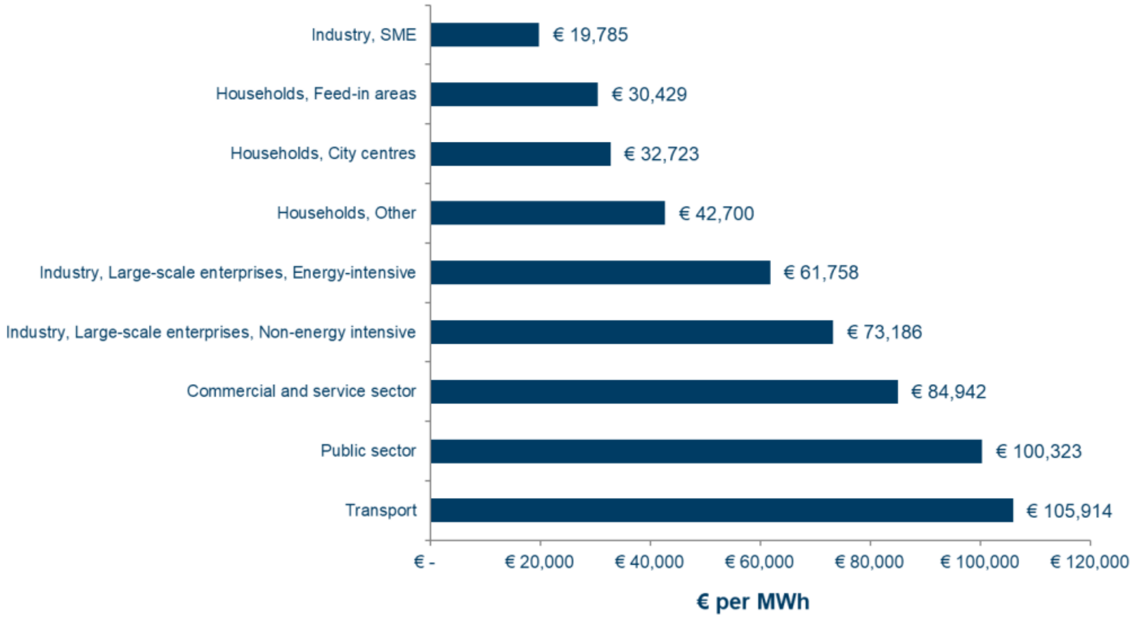
[17] Weare, Christopher (2003). The California Electricity Crisis: Causes and Policy Options

[18] https://www.dallasfed.org/research/economics/2021/0415

Figure 10 Sectoral values of lost load (VOLL) per user category in NL



Source: *ECORYS (2022): The value of lost load for electricity in the Netherlands*

Note: *VoLL for the Netherlands, expressed in €/MWh, following the ACER methodology*

The limited time potential of DSM and the limited surplus electricity for battery charging and pumped storage during prolonged energy shortages mean that large supply gaps will have to be filled mainly by flexible generation capacity, such as flexible power plants using climate-neutral gases.

The TYNDP estimates that around 350 GW of installed flexible power plants using climate-neutral gases will be needed in 2050 under the Distributed Energy Scenario. This implies a need for an additional capacity of around 200 GW (between 600-700 gas turbines of around 300 MW/unit in addition to replacements of existing plants that reached end of life) compared to 2025. These 350 GW of power plants seem reasonable to provide the necessary flexibility for the identified remaining peak loads of between 300 GW and 400 GW, which are conservative given our assumption of a copper plate with no transmission constraints.

In order to close the 107 TWh supply gap identified in Figure 9, these 350 GW of flexible power plants using climate-neutral gases would have to operate for around 300 hours during the 3-week-period in January in question. Over the whole year, the utilisation of these back-up plants will be rather low, as the feed-in of RES-E - if available - will be cheaper (as it has lower short-run marginal costs) than the production of electricity from a flexible power plant.

Conclusion

In conclusion, there will be shortfalls in renewable generation in the future despite the massive increase in RES-E installed. It is extremely important to recognise the extent to which each flexible technology can support the market in a given situation.

Batteries can be very helpful in storing generated renewable energy for a short period of time, but they are not well suited to managing longer supply gaps, with most battery systems having less than six hours of storage. Similarly, DSM can help to balance markets for shorter periods, but industries and consumers would not be able to continuously reduce their demand for weeks at a time (without very high costs). As shown before, interconnectors can be an important source of flexibility in the medium to long term. However, in times of adverse climate events affecting several regions at the same time, interconnectors would not be a viable solution. Finally, flexible power plants using climate-neutral gases are an additional generation capacity that can provide energy at times of peak demand and maintain a level of generation adequacy. Controllable and flexible generation capacity is key to ensuring security of supply in Europe.

We have concluded from our analyses that the 350 GW of flexible power plant capacity using climate-neutral gases required in 2050, as estimated by TYNDP, seems reasonable to provide sufficient back-up capacity. In the next chapter, we will show that flexible generation capacity using climate-neutral gases will in fact only serve as back-up and will not run for most hours of the year.

Flexible power plants using climate-neutral gases will serve as backup capacity running only a limited amount of hours during a year

Flexible, dispatchable generation capacity is able to address a system's flexibility requirements across all timescales as a viable long-term flexible generation technology:

- They can provide reliable and climate-neutral backup electricity and heat to close the supply gap in cold and drought periods when renewable energy sources are not generating enough to meet demand for electricity and heat.
- They are flexible and can easily be scaled up or down to meet different levels of electricity demand, which makes them a valuable tool for balancing the grid.
- They are also relatively inexpensive to build and operate compared to electron-based storage systems.
- They provide ancillary services such as short circuit power, frequency and voltage control, and synchronous condensers which are necessary to maintain the reliability and stability of the electricity grid.

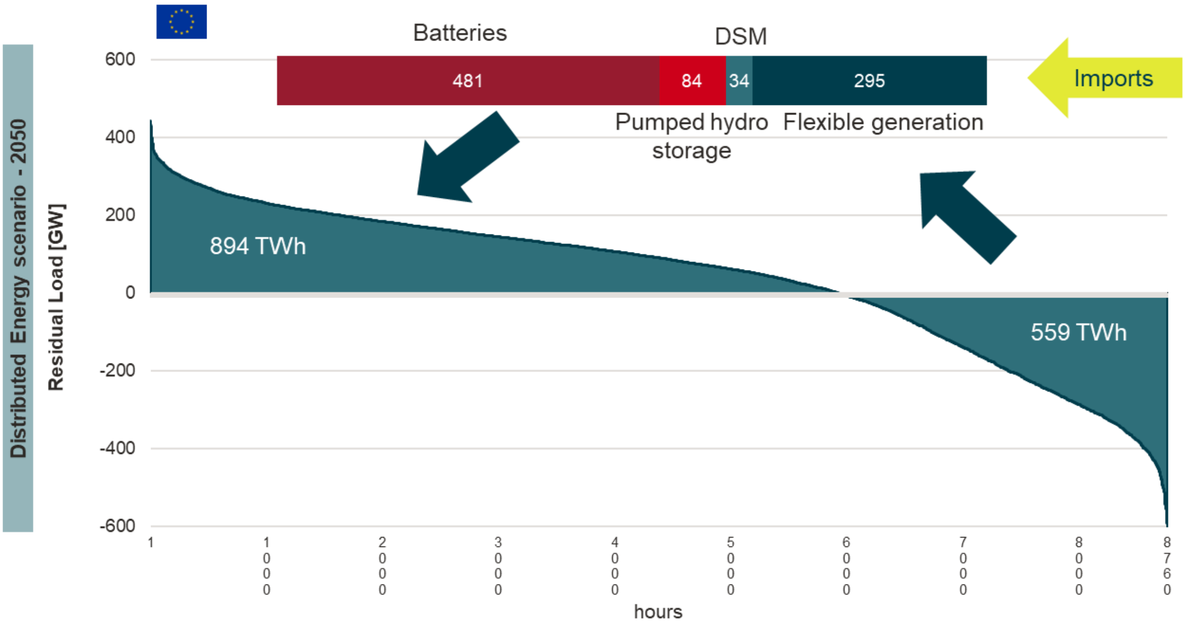
Using examples of periods of very low wind and sun (dunkelflaute), we have shown that large parts of the remaining load will have to be covered by flexible and dispatchable generation capacity. However, over the course of an entire year, these periods will be limited, resulting in relatively low full load hours (FLH) for these plants. They will mainly provide back-up capacity for the system.

Figure 11 shows the residual load duration curve for the EU-27 copper plate example for 2050 under the Distributed Energy scenario for the entire year. The peak residual load is 445 GW, which means that over the course of the year there are hours with even higher residual loads than observed in the presented dunkelflaute in January (Figure 8). The total positive residual load over the entire year sums up to 894 TWh, which will require flexible solutions.

To take into account the contribution from the different flexibility solutions, we take estimations from the TYNDP 2022 modelling results. This is not entirely accurate, given that exact contributions would need to be estimated based on the underlying assumptions such as the weather year in a combined investment and dispatch optimisation modelling, which goes beyond the scope of this paper. Estimates from TYNDP 2022, however, give a good proxy for this exercise.

According to the TYNDP 2022 results, more than half of the 894 TWh would be provided by batteries, i.e. 481 TWh. Shorter supply gaps, e.g. in the evening and at night when the sun is not shining, can be bridged by batteries that are charged during hours of surplus electricity, e.g. at midday. According to TYNDP, pumped storage would contribute 84 TWh over the year, while DSM would reduce demand by a total of only 34 TWh. This would leave about 295 TWh to be provided by flexible generation capacity. Assuming the 350 GW of flexible power plant capacity using climate-neutral gases estimated by TYNDP, this would result in annual full load hours of about 850 hours in a world with perfect transmission between countries.

Figure 11 Residual load duration curve for EU-27 in a copper plate example for the entire year 2050



Source: Residual loads calculated based on TYNDP 2022 data

The approximate 850 FLH for flexible power plants using climate-neutral gases in our example for 2050 must be interpreted with caution, given the extremely optimistic assumption of an unlimited transmission capacity everywhere in Europe (a "copper-plate" approach). It is, however, a lower limit that puts into perspective the FLH estimated by TYNDP 2022. In case of cogeneration plants (where the heat side of the system is made flexible due to heat storage) these cogeneration plants can even provide another additional benefit: providing clean heat can lower the need for heat pumps and thus lower the need for back up capacity for the power system.

The evolution of FLH of the main flexible power generation units for EU27[19] for TYNDP's 2022 scenarios that comply with a fully decarbonised energy system by 2050 are presented in Figure 12. It shows that current full load hour levels for gas plants fuelled with natural gas (e.g. 2,400 FLH in Germany in 2020) will not be reached anymore with increasing levels of renewables. In both the Distributed Energy scenario and the Global Ambition scenario, the

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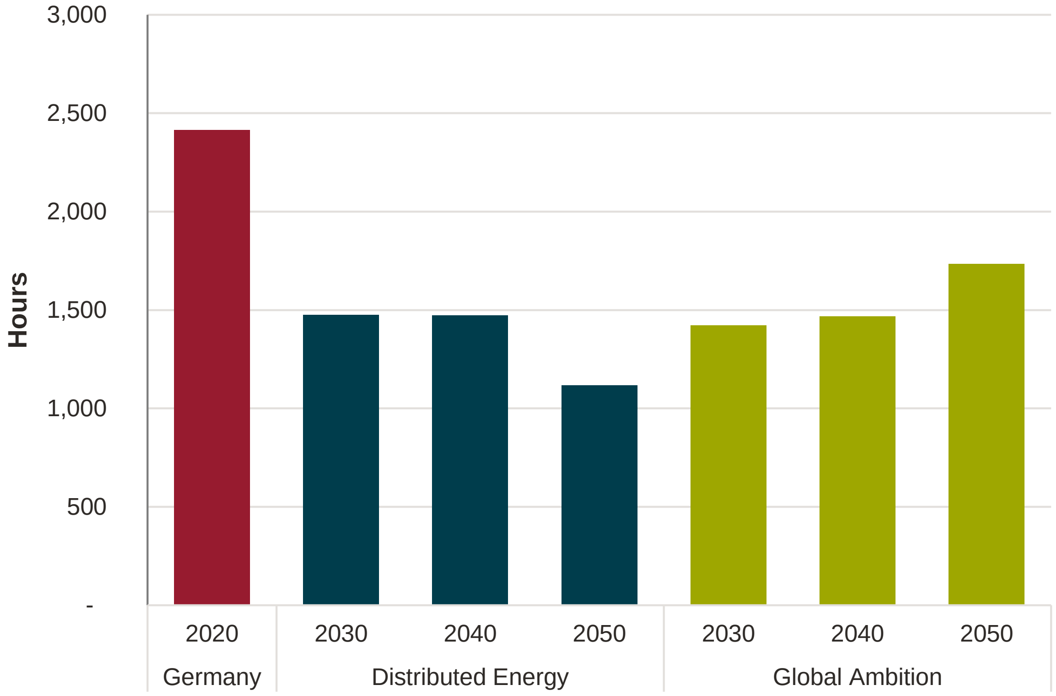
[19] Excluding Small Thermal and CHP which operation can be driven by other factors such as heat production.

FLH falls to around 1,500 per year in 2030 and 2040. In the long term, up to 2050, the FLH in the Distributed Energy scenario continues to fall to around 1,100 FLH. In the Global Ambition scenario, however, a slight increase to 1,700 FLH is expected as a result of the assumed flourishing global energy trade making hydrogen available on a larger scale. However, even in this scenario the current FLH levels are not reached.

Figure 12 Decreasing Full Load Hours of flexible power plants using climate-neutral gases in Europe



Source: Based on TYNDP 2022, current levels from BMWK (2022): Antwort der Bundesregierung auf die Kleine Anfrage Drs.-Nr. 20/633 Fraktion der CDU/CSU zum Thema „Gaskraftwerke in Deutschland – Status quo und geplanter Zubau

Conclusion

In an electricity system that continues to operate on a merit order basis, flexible power plants using climate-neutral gases will only run for a limited number of hours per year, acting as back-up during periods of low RES penetration. Due to the lower short term marginal costs of PV and wind generation, a fully decarbonised electricity system will rely on the largest share of renewable generation. Only at times of low RES input will flexible power plants using climate-neutral gases provide the necessary back-up generation as an "insurance policy".

Policy makers will need to ensure that the adequate investments in the flexible backup capacities like climate-neutral flexible power plants can take place. Therefore, prioritising and investing in green fuel technologies for future-proof gas power plants is critical for achieving a sustainable energy future that supports both economic growth and environmental protection.

Climate-neutral gases are needed to provide low-carbon backup generation

The technology behind flexible power plants using climate-neutral gases is not inherently fossil-based. The fuel source used to generate gas plays a crucial role in determining its environmental impact. While many people think of gas as a fossil fuel, the term “gas” is a broad term that refers to a variety of gases, including green non-fossil gases that are produced from renewable and sustainable sources and have a lower carbon footprint compared to fossil fuels.

These green gases can partly be imported from other world regions with better wind and solar conditions. In pipelines, tanks, or underground caverns, these climate-neutral gases can then be stored for longer periods and used to generate electricity, e.g., in times of dunkelflaute, making them valuable energy storage mediums for seasonal or long-term storage. Complemented by renewable natural gas (e.g., biogas), which is produced through the decomposition of organic matter, such as agricultural waste, food waste, and sewage, climate-neutral gases will play a crucial role in balancing the seasonal feed-in fluctuation gradually replacing fossil natural gas.

While in the near future we will continue to rely on natural gas (fossil methane, imported e.g., from the Netherlands, Norway or the US) for electricity generation, the share of green climate-neutral gas fuels will increase in the mid- to long-term As an interim step, carbon capture, utilisation, and storage (CCUS) technologies will help to reduce the carbon footprint of natural gas until climate neutral gases will be available in large scale. Only these gases which are based on renewable and sustainable sources will prevail to ensure low-carbon power generation. New backup turbines and engines will be "hydrogen ready", meaning that the power plant can switch from methane to hydrogen as soon as hydrogen is available.[20]

In conclusion, it is important to distinguish between different types of gas and to recognise that "gas" is not necessarily a fossil fuel. The sooner green gases are brought to market, the sooner gas power plants will be able to provide renewable and climate neutral electricity to bridge longer supply gaps.

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[20] https://www.eugine.eu/h2-ready/why-h2-ready/

Recommendations to foster investments into climate-neutral longer-term flexibility technologies

Flexibility solutions covering more than a few hours will play a crucial role in a decarbonised energy system that will increasingly rely on intermittent electricity generation. Power plants fuelled by climate-neutral gases provide flexible, firm, low-carbon electricity and will be important to maintain the security of supply – in particular in times of dunkelflaute.

The timely addition of newly build flexible power plants using climate-neutral gases in large scale requires a clear political commitment on both the European but also at Member State level, acknowledging the importance that flexible power plants using climate-neutral gases will play as backup capacity to maintain generation adequacy all over Europe. Flexible power plants using climate-neutral gases are capital intensive investments with technical lifespans that can reach more than 40 years. At the same time the planning and construction of flexible power plants has a long lead time. Only within a clear, reliable and stable regulatory environment, investments will take place in a sufficient manner.

Setting the right regulatory framework to incentivise investments in all technologies needed for the energy transition is crucial. The outcome of the ongoing debate on the reform of the European electricity market design (EMD) will determine whether a resilient European electricity market will prevail.

While the European Commission's EMD proposal, published in March 2023[21], puts a new and much-needed focus on the provision of additional flexibility, there are certain aspects that have not yet been addressed and which could potentially hamper the provision of sufficient backup capacity. In the following chapter, we lay out five recommendations to foster investments into long-term flexibility technologies using climate-neutral gases.

1. Promote all types of climate-neutral flexibility technologies

The recent European Commission proposal strives to enhance the stability and reliability of the European electricity systems. To meet the challenges posed by intermittent renewable energy sources, it is proposed to increase the availability of flexibility solutions. The proposal's emphasis on climate-neutral flexibility solutions is crucial to accommodate the demonstrated growing need for flexibility in the upcoming years. Nevertheless, the suggestion to promote climate-neutral flexibility, in the proposal referred to as "non-fossil flexibility", with a specific emphasis on demand side flexibility and storage, may not adequately address the flexibility needs of the European power system. It overlooks the fact that flexible and dispatchable generation is also necessary to complement energy storage and demand response.

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[21] https://ec.europa.eu/commission/presscorner/detail/en/IP_23_1591

Even though the wording chosen by the European Commission does not exclude flexible power plants as a “non-fossil flexibility” technology per se, the “non-mentioning” leaves room for interpretation which may induce uncertainty among investors whether regulators will further promote investments in urgently needed long-term flexibility solutions. As set out before, gas power plants do not need to run on fossil fuels. A much clearer (technology open) commitment from regulators towards all forms of flexibility will help to avoid disadvantaging flexible power plants using climate-neutral gases .

2. Design a European assessment of flexibility that is technology neutral and focusses on actual flexibility needs

The envisaged **assessment of flexibility needs** as proposed by the European Commission in Article 19c of the “reform proposal to the EU regulation on the internal market for electricity” is a sensible measure to quantify gaps in the provision of flexibility and to increase transparency. By 2025 and every two years thereafter, each Member State's regulatory authority is supposed to evaluate and produce a report on the requirement for flexibility in their electricity system, covering at least a 5-year period. This assessment should consider the necessity of attaining supply security and decarbonizing the power system in a cost-effective manner, while accounting for the integration of various sectors.

However, defining specific national objectives for demand side response and storage based on the report as stated in Article 19d of the European Commission’s reform proposal will not result in a cost-efficient provision of flexibility. Instead, flexibility needs to be thought of more regionally (e.g., Germany has been procuring its flexibility needs from flexible power systems in Austria, Switzerland or Scandinavia for years). National authorities need to ensure that flexibility is fairly priced based on the type of flexibility provided via transparent and competitive markets where possible. The dimensions to be considered shall include the lead/ramp up time, the duration flexibility can be provided, the location where the flexibility is needed as well as requirements on the carbon neutrality.

Also, flexibility assessments should distinguish not only between seasonal, daily, and hourly flexibility, but also include weekly needs. A much more granular definition of the required flexibility will help to provide all different kinds of flexibility needed. By taking a more technology neutral approach that is focused on the actual system needs than on specific technologies, a more cost-efficient provision of needed flexibilities can be ensured. On the contrary, a premature exclusion of certain technologies would induce inefficiencies.

3. Ensure sufficient and fair income from reliable revenue streams

Investors in long-term flexibility solutions need clarity on the **envisaged remuneration mechanism** for their investments. For example, power plants that provide flexible, firm and low-carbon electricity will serve mainly as backup capacity, running on a limited amount of hours. Still, investments are capital intensive and need to generate sufficient income from reliable revenue streams to cover not only the short run marginal costs (SRMC) but also the CAPEX and fixed costs for operation and maintenance (O&M).

One guiding principle should be that **all services provided are paid for** which means fair remuneration for electricity generation, capacity availability and ancillary services:

- **Energy price mechanisms**: Revenues from selling electricity on the electricity markets (in €/MWh) are one main revenue stream for generation capacities. In general, pricing on the day-ahead market based on a “merit order” with “pay-as-cleared” is the typical pricing for any homogeneous commodity (and thus also for "electricity") and ensures the optimal use of available electricity plant capacities. This sends the right scarcity price signals to the market participants, which lead either to demand adjustments and/or to investment signals for new capacities. In a world with decreasing hours in which firm backup capacity is needed, investors are dependent on sufficient rents in those few hours where they operate. This makes a functioning price mechanism signalling scarcity indispensable. It is thus very positive that the European Commission’s EMD proposal preserves the merit order principle. This was not necessarily to be expected after the strong criticism of the merit order principle following the spill-over of gas price increases into electricity markets. Still, the questioning alone of the marginal pricing within the EU has disturbed investor’s confidence in the markets. Rebuilding this confidence through a clear commitment to a functioning price mechanism based on the merit order principle is important. The EMD proposal is a step in the right direction.

- **Capacity price mechanisms:** Within capacity mechanisms, payments are made for the pure availability of generation capacity (€/MW). They present a second possible income pillar for firm backup plants. Availability is becoming much more important in an energy system that increasingly relies on intermittent electricity generation and should thus be remunerated. In this regard, is has to be welcomed that the European Commission proposes introducing additional criteria or features in the design of existing capacity mechanism to promote the participation of non-fossil flexibility (Article 19e). Again, as stated before, the non-mentioning of other flexibility solutions than demand side response and storage must be criticised as it leaves ambiguity over whether long-term flexibility solutions such as flexible power plants using climate-neutral gases may be included. The same applies to the mentioned flexibility support schemes consisting of payments for the available capacity that could be implemented by Member States if no capacity mechanism is in place or if the additional criteria to promote the inclusion of flexibility solutions will not be sufficient (Article 19f). As already said, a clearer commitment towards all forms of flexibility within the EMD proposal will help to avoid disadvantaging flexibility options such as climate-neutral flexible power plants. Furthermore, it is not clear how flexibility support schemes shall comply with state aid rules and how they shall coexist with existing capacity mechanisms. In any case, newly implemented flexibility schemes shall be designed in a technology neutral way and focused on actual flexibility needs.

- **Price mechanisms for ancillary services**: To ensure grid stability, ancillary services, including frequency control, voltage support, reactive power supply or black start capability, play a crucial role and must be compensated fairly. Offering foreseeable and equitable payments, whether through market-based payments or regulated prices, will help to foster investments in flexible generation capacity based on renewable fuels. If there is a need for new investments in instantaneous reserve products such as "rotating masses" from a system perspective, then this "service" must also be compensated.

4. Synchronise and accelerate the provision of climate-neutral fuels, and electricity and hydrogen generation and transmission infrastructure

Gas power plants are not necessarily operated with fossil fuels. The origin of the gas plays a crucial role in determining its environmental impact. A variety of gases exist, including green non-fossil gases that are produced from renewable and sustainable sources and have a low carbon footprint.

The sooner the share of green non-fossil gas increases, the sooner low-carbon power generation from flexible power plants will become a reality. In this regard, it is important that approval and permitting procedures for all infrastructure (electricity, hydrogen production and transmission) are accelerated. Furthermore, the sufficient provision of climate-neutral fuels needs a clear and reliable certification system and the possibility to enter long-term commitments. Single buyer models like the German Hint.Co[22] as intermediary absorbing parts of the volume risks are promising and could also lower the certification risk (i.e. the risk of hydrogen not being labelled as green) significantly. Finally, the access to capital markets needs to be clear for all market participants. Obligations on sustainable financing like the EU Taxonomy should be aligned to fuel availability.

5. Rebuild trust by providing a stable regulatory environment for investors

Following the energy price crises in 2022, policy makers all over Europe have induced a high level of uncertainty regarding the future functioning of the European electricity market. For example, proposals like the splitting short-term markets from Greece, the questioning of marginal pricing by several European politicians and regulated prices for inframarginal technologies (Spanish proposal) have made it difficult to build reliable business cases for electricity generation and flexible technologies.

In this regard, the EMD reform proposal should be seen as a first step towards rebuilding trust by trying to protect the basic principles of the functioning of the European electricity markets, notably short-term markets based on marginal pricing. It will be important that in the following

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[22] Hintco is a subsidiary of the non-profit H2Global Foundation. It core tasks are the structuring and implementation of competitive bidding processes for the purchase and sale of green hydrogen-based products, the contract management, the monitoring and reporting on the compliance with the contractual requirements and the call-up and disbursement of funds as part of the payment process.

debates and negotiations with the European Parliament, the Council and Member States basic market principles will not be questioned again. Otherwise, planned investments in generation capacities will be postponed or completely dismissed.

Furthermore, European policy makers have a history of implementing policies devaluating assets in firm dispatchable capacities. Mandatory nuclear and coal phase outs in different Member States have significantly reduced the respective asset values. In addition, uncertainty around compensation schemes for business models that have been outlawed often have ended in front of courts (e.g. Vattenfall case[23] after the nuclear phase out in Germany) and have further reduced trust in the regulatory certainty and the protection of investments within the European electricity markets.

For investors in flexible power plants running on climate-neutral gases, the availability of climate-neutral fuels will be a key point when taking the decision to go forward with an investment. In addition to the availability of renewable and climate-neutral gases, the access to required transmission infrastructure will also play a role.

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[23] https://www.bmwk.de/Redaktion/DE/Artikel/Energie/vattenfall-gegen-bundesrepublik-deutschland.html

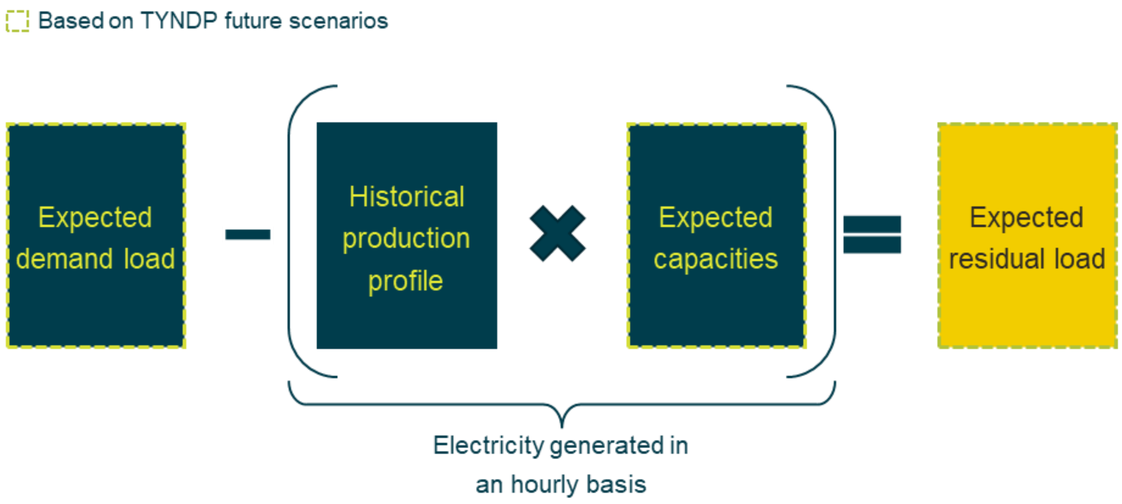
Annex A – Technical details on the modelling approach

Our model attempts to estimate the total hourly residual load, which we define as the hourly demand load minus the electricity generated by nuclear, offshore wind, onshore wind, solar PV, run-of-river, other renewables and other non-renewables.

We carry out this analysis for individual countries in the EU and clustered countries (e.g., EU-27 all together) based on scenarios developed by ENTSO-E "Ten Year Network Development Plan" (TYNDP) 2022 report, which predicts estimations up to 2050. Data is collected by TYNDP 2022 in the download section on its website.

The TYNDP 2022 entails two future scenarios picturing pathways achieving EU-27 carbon neutrality by 2050: The "Distributed Energy" and "Global Ambition" scenarios. Within the Distributed Energy scenario carbon neutrality is secured with a high degree of European autonomy with maximization of renewable energy production in Europe and a strong decrease of energy imports. Within the Global Ambition scenario energy imports are much more relevant due to a global move towards the Paris agreement resulting in flourishing global trade of energy. We used both scenarios to picture future energy markets within the EU.

Figure 13 Our model in a nutshell



Source: *Illustration of Frontier modelling*

Figure 13 explains the model approach in simple terms. First, TYNDP provides demand time series for each scenario for the years 2030, 2040 and 2050 for each individual country in the EU. Moreover, within the time series, it is possible to select for each country the desired climate year for the demand, in which it does not impact the total amount of electricity demanded but the demand profile of that year. It is important to note that we have chosen the demand climate year 2009 as it ranks second as the most stressful year after 2012 in terms of two-week dunkelflaute period with low wind load factors and solar radiation.

Second, we use historical production profiles based on Pan-European Climate Database (PECD) developed by ENTSO-E for solar, wind offshore and wind onshore to capture weather years. These datasets get regularly updated as part of seasonal outlooks. For other electricity sources, we use an internal approximation based on capacities and dispatch data from TYNDP. Production profiles for RES-E can be seen as representative to capture the natural climate variability of that climate year, in essence, strong and weak wind years. A climate year can vary significantly – there are years where RES-E production aligns relatively well with power demand but there are also many years with very low output from wind in solar for several weeks in a row – despite huge installation numbers and wide regional spreading of the RES-E units across Europe.

Third, production profiles are multiplied by the forecasted capacities provided by TYNDP in order to calculate the hourly generated electricity. As we can see in Table 1, capacity changes depending on the scenario and year ahead we chose for the EU-27 countries. Both demand and capacities will be selected on the same climate year and scenario in order to provide accurate estimates. As a result, we obtain the hourly generated electricity for each energy source to reflect hourly generation in the future.

Table 1 Expected capacities based on TYNDP's future scenarios

		Distributed Energy scenario	**Global Ambition scenario**
Run-of-River		*In GW*	*In GW*
	2040	173.4	173.4
	2050	173.4	173.4
Nuclear			
	2040	45.4	97.5
	2050	18.8	85.9
Other Non RES*			
	2040	33.6	33.6
	2050	33.4	33.4
Other RES**			
	2040	37.3	37.3
	2050	36.4	36.4
Solar PV			
	2040	1160.5	840.4
	2050	1582.8	1047.3
Wind Offshore			
	2040	200.4	255.9
	2050	298.5	341.9
Wind Onshore			
	2040	662.5	433.2
	2050	846.5	539.3

Source: Based on data from TYNDP 2022

Note: *The capacities are a sum of EU-27 countries. Capacities values of the summed of EU-27 countries. *Other RES includes bio-fuels, marine, geothermal, waste, and any other small renewable technologies. **Other non-RES includes mainly CHP that is used in district heating and industry.*

We then sum generation from all technologies within the model and subtract from total demand on an hourly basis to obtain hourly residual loads for each country in a given scenario for a specific period. Residual loads greater than 0 means that demand is not being met by the listed technologies alone (e.g., RES-E, nuclear) and therefore, other backup capacity, storage and/or DSM are needed. Conversely, residuals lower than 0 means generation meets the required demand and produces more than it needs, making it possible to store or to export.

Finally, we explicitly look at the periods with low RES-E production due to the weather conditions to analyse the "gap" in electricity occurring in these so-called "dunkelflaute" periods which can last for several days or even weeks. Figure 8 shows duration curves for the month of January based on different production profiles years. Table 2 summarises the results per each representative year for Distributed Energy scenario in 2050.

Table 2 Duration curve results for January 2050 as presented in Figure 8

Weather year	Sum of positive residual loads	Sum of negative residual loads	Difference	Peak residual load	Mean residual load	Minimum residual load
	in GWh	*in GWh*	*in GWh*	*in GW*	*in GW*	*in GW*
1990	82,727	-19,576	63,152	407	85	-341
1995	61,121	-26,823	34,297	345	46	-331
2000	91,228	-18,490	72,738	401	98	-367
2005	63,873	-26,001	37,872	313	51	-356
2010	125,115	-6,382	118,734	366	160	-334
2015	84,751	-18,224	66,527	418	89	-324

Source: *Based on data from TYNDP 2022*

Note: *Based on Distributed energy scenario for January month in 2050 with different representative production years (first column)*

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