Flexibility solutions to support a decarbonised and secure EU electricity system

Version: 01
Date: 20 October 2023
EEA activity: 2.1.4 Energy system: knowledge development

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Acknowledgements

This report was prepared by a mixed team of authors on behalf of the European Environmental Agency (EEA). The authors of the report were Mihai Tomescu, from the EEA, and Victor Juarez and Søren Møller Thomsen, from Ramboll, who implemented the detailed quantitative analysis. Contributions from Ils Moorkens and Marco Ortiz Sanchez, from the European Topic Centre on Climate Change Mitigation have played a central role in preparing this report and some of its case studies.

We are also grateful for support and guidance received from Daniel Ihasz Toth, Florian König and Aleksander Glapiak, from the EU Agency for the Cooperation of Energy Regulators (ACER), in both writing the report and undertaking the quantitative analysis.

The authors would also like to acknowledge the EEA Eionet member countries and collaborating countries, the regulatory authorities network cooperating with ACER, the European Commission Directorate Generals CLIMA and ENER, along with other EEA experts, for having provided valuable comments to the draft report.

1 Background

The EU and its Member States are moving towards a climate-neutral future. Significant policy efforts are being directed towards replacing fossil fuels with renewable energy sources across the energy system, so that by 2030 GHG emissions can be reduced by 55 % at EU level (compared with 1990). With renewable electricity being a key component to help decarbonise also other end-uses, such as heating and transport, the share of intermittent renewable generation sources like solar and wind power must grow very rapidly towards 2030. This means however that future electricity production will fluctuate more than currently. To ensure security of supply and reduce the risk of power failures when generation from solar and wind is low, the flexibility of the electricity system must be enhanced considerably[1].

The purpose of this report is to draw attention to the dual challenge policymakers and investors face this decade: To increase the deployment of renewable electricity supply while equally maintaining energy adequacy. The report includes the following elements:

1. A general introduction to the electricity sector in Europe, which covers the main developments since 2010 until today, and look forward towards 2030 listing the challenges and solutions for a continuous increase of renewable electricity production as we see them today.
2. Quantitative analyses to estimate the complementarity effect from wind and solar, the expected residual demand and the associated flexibility needs in the future electricity system with much higher levels of renewable energy production following the climate targets across Europe to expand renewable energies[2].
3. Four case studies that each highlight a set of feasible solutions to ensure security of electricity supply as part of the green energy transition.
4. A set of policy toolboxes and recommendations focusing on the need for flexibility solutions in relation to infrastructure, supply, demand, and storage. The recommendations build upon the findings in previous chapters.

1.1 Decarbonisation and energy independence objectives

To respond to the climate challenge, in 2020, the EU Council increased EU's binding climate target for 2030 from a 40 % to a 55 % reduction in GHG emissions, compared with 1990 levels, ending in net climate neutrality by 2050 (EU, 2021). To meet this target, the European Commission (EC) has proposed changes to the climate and energy legislation under the 'Fit-for-55' legislative package of 2021, which are currently subject to the EU legislative process.

Following Russia's invasion of Ukraine in February 2022, the geopolitical context has changed in Europe, impacting the EU`s ambitions for the energy transition. The present situation has not only renewed calls to enhance energy efficiency and diversify the EU's energy resource suppliers, but also to accelerate the expansion of renewable energy sources to end the EU's dependence on Russian oil and gas well before the end of this decade (EC, 2022a). At present, Member States are in the process of updating their national energy and climate plans, reflecting on further opportunities to implement energy conservation measures and boost renewable

[1] The environmental impact from renewable energy is not considered in this report, the focus being solely on flexibility needs in a future EU electricity system that is climate compatible and secure.

[2] Important terminology and a full list of abbreviations are listed in Section 6.

energy supply in line with the new 55% GHG reduction target, including sectors with a traditionally high dependence on fossil fuels.

The European electricity market developed to promote liberalization, integration, and the energy transition while ensuring electricity supply. Legislative packages, including the Energy Regulation and Directive, shaped the internal market, considering sustainability goals (EC, 2019c). The European Commission proposal on Electricity Market Design is set to amend the Electricity Regulation, adding emphasis on security and flexibility elements.

1.2 Security of supply with renewables and flexibility resources

As the integration of European electricity markets has progressed, few imagined that security of supply and EU energy independence in general would become high pressure issues in a not-so-distant future. However, Russia's manipulation of gas supplies and invasion of Ukraine has changed that picture. Concerns over the availability and reductions in supply of fossil fuels for electricity generation drove electricity prices to record high levels impacting both industrial and private consumers in addition to raising questions about the ability to maintain an adequate level of energy supply in years to come.

The internal European electricity market is equipped with a coordinated framework to prepare for and manage risks and to assess and tackle resource adequacy issues. However, the impact of an enduring external shock of a geopolitical nature may require additional policy measures both to temporarily mitigate the immediate impact of the energy crisis and to adapt to the changes set in motion by the energy crisis. While energy efficiency measures are an effective measure both on the short and long term, to manage the necessary adaptation process, the debate over *quick fixes* and *long-term solutions* should be separated.

For the immediate term, Member States, and the EC are working with international partners to find alternative supplies of gas, oil and coal and nuclear fuel. At the same time, energy savings and energy efficiency measures are thought to be perhaps the largest available resource. Behavioural changes of business and end-consumers can make a significant difference, as visible in practice during the last quarter of 2022 (Oliver Ruhnau et al., 2023). The EU gas consumption has dropped by 19% (weather-corrected) in the period August 2022-January 2023, compared with the average gas consumption for the same months between 2017 and 2022 (Eurostat, 2023b). Hence, when examining the energy supply and end-use sectors, and the plans to upscale renewable energy, the electricity system is not the whole story, yet an increasingly important component of the EU energy system. As such, this report has a focus on integration of renewable energy in the electricity system to support decarbonisation and reduce energy import dependency.

As early as at the beginning of March 2022, the EC clarified in its REPowerEU Plan (EC, 2022m) that the transformation of the electricity system towards carbon-neutrality remains a key priority. Renewables are the cheapest and cleanest energy available and reduce the EU`s need for energy imports[3]. Accelerating the deployment of renewable energy is expected to bring down emissions and promote energy independence.

[3] It must be noted that renewable technologies and batteries are made of minerals that today are extracted outside of the EU. The Green Deal Industrial Plan with the Net-Zero Industry Act and the forthcoming Critical Raw Materials Act tackles this issue to ensure sufficient access to those materials, like rare earths, that are vital for manufacturing key technologies (European Commission, 2023).

2 The electricity sector in Europe: challenges and solutions towards 2030

This chapter describes the current electricity system in Europe and the changes since 2010. Furthermore, it highlights the rapid transformation the system must undergo this decade to ensure both climate mitigation and energy security concerns by 2030.

Together with historic data, we are presenting three different climate and energy scenarios from the European Commission with targets for 2030 for delivering the European Green Deal (EC, 2021e). This sets the scene for where we have been and how far we must go to reach the 2030 climate and energy targets as well as how renewables must grow to play the largest role.

2.1 Main trends

Renewable energy sources (RES) increased significantly over the past decade; but even so, higher deployment rates are needed during this decade.

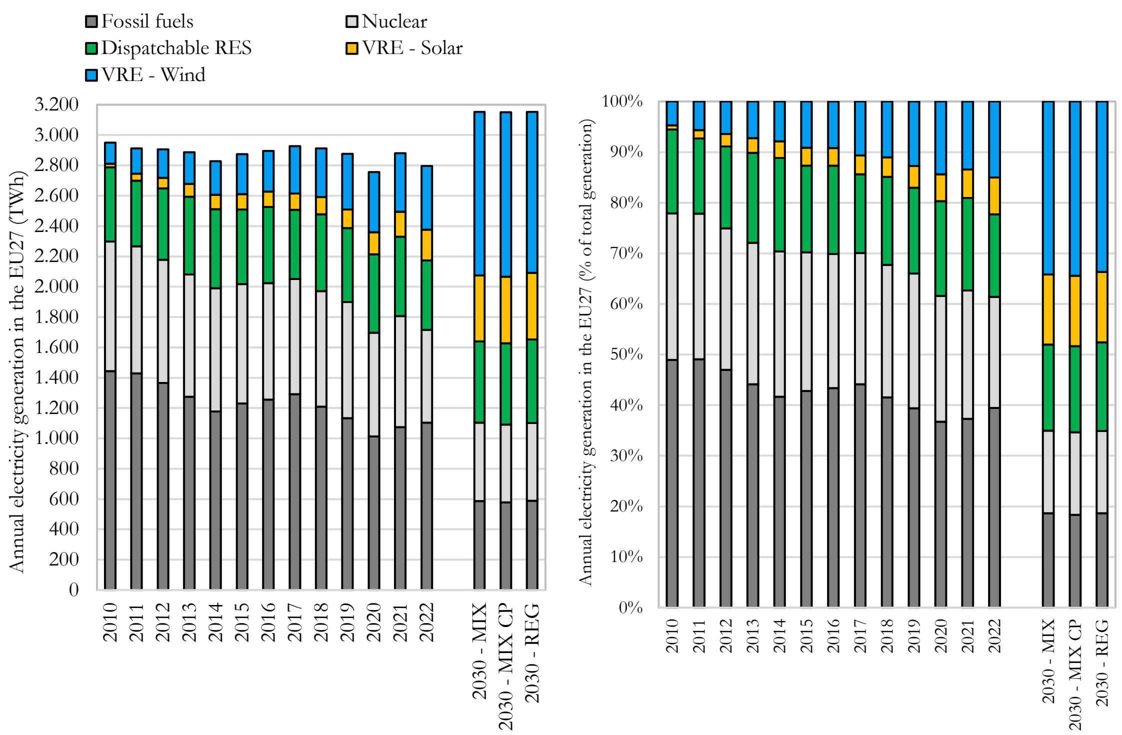

Figure 2-1: Electricity generation in the EU27

Sources: Historical data from ENTSOE transparency platform **(ENTSO-E, 2022d)**; 2030 projections from the Policy scenarios for delivering the European Green Deal built upon the Climate Target Plan **(EC, 2021e)**.

Notes: Dispatchable renewable energy sources (RES) includes hydropower, bioenergy, and other renewables.

As shown on Figure 2-1, the European gross electricity consumption (coincident with gross generation[4]) has been rather stable since 2010, except for a decrease in 2020 due to COVID-19, and a lower demand in 2022 following demand reduction measures implemented across the EU and driven by high electricity prices (Ruhnau et al., 2023). Over the last decade, renewable electricity generation from wind and solar has increased and replaced nuclear and fossil fuel generation. Between 2010 and 2022, generation from wind and solar more than tripled from 163 TWh to 623 TWh. The generation from hydro power, bioenergy, and other renewables has been almost stable. The fossil-fuel and nuclear generation has decreased by 25% (1,443 TWh fossil fuels and 854 TWh nuclear in 2010, 1,104 TWh and 613 TWh in 2022).

In 2010, wind and solar accounted for 6% of total EU electricity generation. Yet, in 2022 they increased to 22%. The fast deployment of wind and solar has been driven by national targets and support schemes, even if projects without subsidies have been possible in recent years thanks to a decrease in development costs. From 2010 to 2021, the levelized cost of electricity (LCOE) generation fell by 85% for solar PV, 56% for onshore wind and 45% for offshore wind (IRENA, World Energy Transitions Outlook 2022).

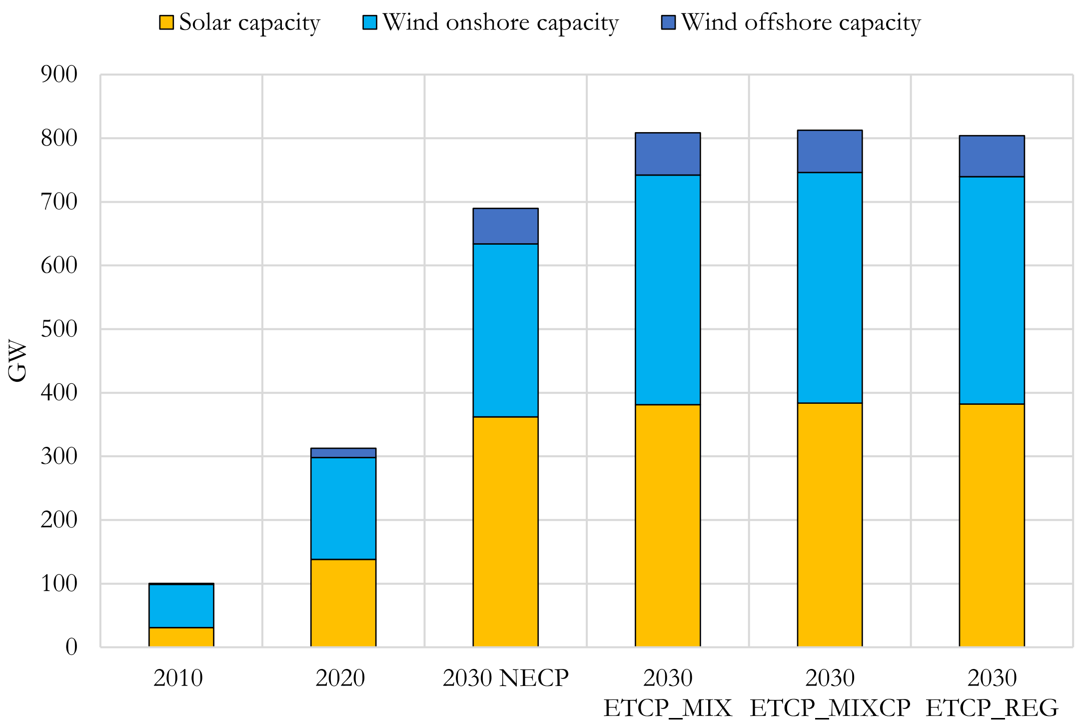

Figure 2-2: Solar and wind capacities in EU27 in 2020 and 2030

Sources: (1) Eurostat detailed shares for 2010 and 2020 capacities; (2) 2030 NECP: final NECPs 2030 capacities; (3) 2030 ETCP_MIX, 2030 ETCP_MIXCP and 2030 ETCP_REG: policy scenarios for delivering the European Green Deal built upon the Climate Target Plan **(EC, 2021e)**.

Notes: (1) For some Member States only production data were available in final NECPs. In these cases, capacities were calculated from production data taking into account average full load hours for 2016-2020 from Eurostat detailed shares for wind or from Global Solar Atlas GSA 2.7 for solar energy; (2) For France only data for 2023 and 2028 were available in the final NECPs, requiring the extrapolation of the trend 2023-2028 to 2030; (3) For Latvia no 2030 capacities were available from the NECPs and 2020 capacities were taken as approximate.

[4] Excluding auxiliary consumption of power plants and cross-border import/export.

According to the EC policy scenarios for delivering the European Green Deal built upon the Climate Target Plan (EC, 2021e), from 2022 to 2030, final electricity consumption will increase by 13% in all scenarios, at the same time as the EU will reduce its levels of primary and final energy consumption in absolute terms, through energy efficiency improvements. The expected increase in electricity demand would be driven by direct electrification of end-use sectors (such as heat pumps and electric vehicles) and, where direct electrification is not feasible, by indirect electrification through Power-to-X (PtX), such as in high temperature industry, heavy road transport, maritime transport, and aviation.

Electricity generation would have to increase accordingly, with generation growth expected to come mainly from variable renewable energy (VRE) generation. In all EC scenarios, VRE generation is estimated to supply 50% of the gross electricity demand by 2030 (EC, 2021e) with a total annual generation of 1,512 TWh, on average, for all scenarios (see Figure 2-1). In practice, this means that VRE generation must increase every year by 111 TWh, on average, which represents almost three times as much as the average annual VRE growth recorded from 2010 to 2022 (+38 TWh per year). While dispatchable fossil fuel generation is expected to decrease in a future system dominated by VRE, to avoid blackouts, the transition towards a clean and secure electricity system must incorporate a sufficient mix of flexibility resources, including demand response, cross-border interconnectors, energy storage, as well as other decarbonised dispatchable forms of generation.

The accelerated deployment of renewable energy and electricity sources towards 2030 are shown in Table 2-1. The EU's renewable energy share must reach 42.5% of final EU energy use by 2030, with each Member State being able to add additional 2.5 % to that target, as renewable electricity generation increases to 69% by the same year (European Council, 2023). According to the 2030 EC Climate Target Plan, the share of intermittent solar and wind power capacity in 2030 would increase to between 58 % - 61 % of all electric capacity in the EU electricity mix (EC, 2020b).

Table 2-1. Acceleration of renewable energy deployment in EU Green Deal and REPowerEU

Concept	EU Green Deal EU Climate Target Plan	REPowerEU (2022)
Binding share of renewable energy use in EU gross final energy consumption in 2030	40%	(45%) 42.5 % + 2.5 % (*)
Associated share of renewable electricity generation across the EU in 2030	65%	69%

Note: (*) 2.5% represents an additional indicative top-up that would allow the EU to increase renewable energy sources to 45% of its gross final consumption by 2030.

Demand for electricity is expected to increase, as industry, transport, heating, and cooling are electrified, together with emerging electricity consuming sectors such as Power-to-X (electro-fuels for transport and industry) and data centres. Today, most electricity demand is inflexible, and this must change; demand must become more responsive to the growing variability of RES generation.

Figure 2-2 shows the solar and wind capacity development in the EU for 2010, 2020, 2030 according to the national energy and climate plans, and 2030 according to the policy scenarios delivering the European Green Deal.

National energy and climate plans (NECPs) from 2019 have detailed the intended contributions from each Member State to reach the previous EU renewable energy consumption target for 2030 of 32%. For 2030, the current national contributions result in a total renewable energy share of between 33 % and 34 % at the EU level (EC, 2021a) and in more than a doubling of the VRE capacity (from 312 GW in 2020 to 690 GW in 2030). The largest relative growth is planned for offshore wind, which is expected to almost quadruple its capacity by 2030, compared with 2020. Solar PV capacity would increase by 2.6 by 2030 and onshore wind capacity by 1.7, compared with their respective levels in 2020.

As such, according to the 2019 NECPs, solar PV will account for more than half of the variable renewable energy capacity in 2030, onshore wind for almost 40% and offshore wind for around 10%. However, according to the EC policy scenarios for delivering the European Green Deal (see Climate Target Plan, (EC, 2021e), the capacity of solar and wind energy must increase by 100 GW more than what countries had foreseen in 2019 in their NECPs. This means that Member States need to set higher renewable energy goals. If annual renewable energy deployment rates from 2010 to 2022 were maintained, renewables would reach a mere 29% share in final EU energy consumption by 2030, and a 50% share in EU electricity consumption by the same year. This, in the context where REPowerEU has outlined the necessity of moving towards higher shares of renewables in total energy consumption and electricity generation, to replace Russian gas (see Table 2-1). By June 2023, Member States must submit updated NECPs, reflecting these higher levels of ambition for 2030.

Based on the national and EU roadmaps and scenarios, three important trends emerge:

1. In several European regions, the share of renewable energy sources (RES) is increasing at a fast pace and must continue to do so in the coming years to meet climate and renewable energy targets. The fastest growing sources of electricity generation are variable renewable energy sources (VRE, wind and solar), which are intermittent by nature.
2. The growth in RES will complement the phase out of dispatchable conventional fossil fuel generation. Several EU Member States have announced or decided on the administrative phase-out of coal. In most cases, the entire coal phase-out is likely to be achieved by 2030 or earlier, with a few notable exceptions such as Germany and Poland (depending on current policy decisions and their implementation).
3. To decarbonize other sectors, such as buildings and transport, electrification will increase in importance as a very effective and cost-efficient solution, leading to an increase in final electricity consumption by 2030, despite energy efficiency gains ([5]) (EC, 2021b)

Together, these three trends will pose challenges, as electricity generation and demand must be balanced. Reflected by periods of high and low generation and fast ramp-ups and -downs, the intermittency of VRE sources will bring new challenges to match supply and demand.

[5] According to the EC impact assessment up to 11% in 2030 compared to 2020.

2.2 Challenges

To counteract the fluctuations of VRE, the energy system needs sufficient flexibility provisions (Brunner et al., 2020). As of now, VRE fluctuations can be absorbed in the grid with existing solutions. Nevertheless, the high pace of VRE growth needed this decade will exert greater intermittency problems which, if left unmanaged, will cause problems in the operation of the electricity system. The latest European Resource Adequacy Assessment by ENTSOE calls for an increase in flexibility resources to address resource adequacy issues (ENTSO-E, 2023). The flexibility mechanisms that can support higher shares of intermittent RES integration into the energy system are grid extension and increased interconnectivity, dispatchable generation (and, for the time being, also curtailment) and energy system integration, including demand-side response and energy storage. Current and future policy designs need therefore to consider ways of increasing all sorts of flexibility across the EU electricity system.

2.2.1 Energy adequacy

Under decreasing shares of dispatchable generation and increasing shares of VRE, the electricity system adequacy must be ensured with decarbonised flexibility resources available from generation, demand side response and storage in an integrated and interconnected EU energy system.

As the share of VRE generation in the European electricity system increases, so does the need for flexibility resources to compensate for weather-dependent fluctuations in generation and to ensure the stability of the electricity system. Currently, the predominant resources of flexibility are dispatchable generation (thermal capacity and hydropower) and interconnectors (together with a very limited share of active flexible demand). The stable and secure operation of the electricity system with adequate resources to balance the system at all times in the future are not currently in place (Denholm et al., 2021).

In addition to the flexibility provided by dispatchable generation and interconnectors transporting renewable electricity across grids, demand-side flexibility can become a key flexibility resource at all timeframes in the near future, supporting VRE integration along with other options such as energy storage (Cruz et al., 2020). Moreover, flexibility options can include electrolysers increasing production of green hydrogen, for instance when renewable generation exceeds demand, electric vehicles adapting their charging patterns to the needs of the system, or insulated buildings that shift their heating and cooling needs to more optimal timeframes with the help of ICT and artificial intelligence (AI) via domestic or industrial heat pumps or district heating. Curtailment can be used as a last resort to attain the balance between generation and demand, as it has a cost for the system and reduces the incentives to invest in more renewable energy (Delarue and Morris, 2014).

To better understand the flexibility needs of the future European electricity system, this report undertakes a quantitative assessment of the variation of residual demand (the difference between demand and VRE generation) in the European electricity system based on historical data as well as for prospective VRE levels by 2030.

For 2030, the analysis finds that an increase of 240% of VRE generation, compared with 2021 levels[6], will require more than the doubling of the flexibility provisions existing in 2021 across the EU electricity system. Over the period 2015-2021, the average daily, weekly, and annual flexibility needs were 157 TWh, 128 TWh and 130 TWh, respectively. In 2030, when VRE installed capacity should be at least 3.4 times higher than in 2021, daily, weekly and annual flexibility needs are estimated to reach 362 TWh, 242 TWh, and 168 TWh, respectively [7]. Essentially, for daily, weekly and annual flexibility needs this means an increase of 138% (2.4-fold increase), 77% (1.8-fold increase) and 28% (1.3-fold increase), compared to the situation in 2021.

As in **(EC, 2019g)** or **(Koolen, D., De Felice, M. and Busch, S., 2023)**, this report finds a steep increase in flexibility needs towards 2030, especially on a daily basis. Equipping the European electricity system with all possible flexibility resources is therefore as important as investing in renewable generation sources, in order to ensure the system will be able to cope with short, medium and long-term fluctuations of VRE generation and inflexible demand (not all demand can be fully flexible). Policies enhancing a faster deployment of flexibility resources must be designed and rolled out timely. Such policies can point at direct regulation, market design, fiscal policies, support schemes as well as grid regulation.

An example of direct policies are the new framework guidelines on demand response, the draft version of which is under consultation (ACER, 2022c). On the market design, it is important that the market provides the adequate price signals to incentivise the investment in flexibility resources like storages and demand response technology enablers (metering and submetering and communication equipment). The business case for storage and demand response relies on the price differentials between periods of charge to periods of discharge (consumption increase and decrease respectively). Demand response can also be incentivised with dynamic tariffs to make consumers price-sensitive **(EC and Guidehouse, 2021)**.

However, as excessive price volatility can be problematic to many final consumers, the right balance must be found between the short-term price exposure of consumers and fixed-price contracts that protect consumers from excessive price peaks. Fiscal policies can, for example, reduce electricity taxes when electricity is being consumed for heating (see e.g. Denmark, **(SKAT, 2023)**), in order to incentivise a swifter move away from gas-based heating via electrification.

Regarding grid regulation, special conditions may be needed for storage in order to avoid double-charging of grid tariffs (i.e. charging the same electricity twice, when withdrawn and then reinjected into the grid) **(Council of European Energy Regulators, 2020)**. Also, on grid regulation, a rapid deployment of smart meters (and sub-meters), which enables access to granular data for all end-consumers, can foster demand response and sector-integration via more active end-consumers. End consumers with dynamic tariffs can react to price signals and adapt (to a certain extent) their demand patterns to the system needs. It is however a prerequisite that a smart meter count with the right functionalities laid down in Article 20 of

[6] Corresponding to three main target-reaching scenarios of the EU Climate Target Plan (EC, 2021e).

[7] Under the scenario with existing and planned interconnectors and the reference demand projection. See Chapter 3 for details on the analysis and scenarios simulated.

Directive (EU) 2019/944, (two-way communication, high time-resolution, accessible granular data, etc.).

Furthermore, decentralised energy resources (DERs) can offer vast potential for additional flexibility in the system by using already existing technologies (e.g., electric vehicles and heat pumps), and therefore should receive increased attention in the future. Already today, DERs can participate through aggregation in balancing and other ancillary services in different countries, including across the EU. The fourth case study, in chapter 4.4, showcases a pilot project that allows the participation of these resources pooled into balancing service groups (virtual power plants) that provide ancillary services in Italy.

2.2.2 Balancing services

Growing shares of VRE generation require more flexibility to provide increasing balancing services and improved inertia in the system.

Balancing services and frequency regulation services are used to restore the supply-demand balance in electricity systems whenever there are frequency deviations originated by a generation-demand mismatch. The inherent weather-dependency of VRE inevitably brings forecasting errors that result in actual dispatch deviations from net positions settled in the day-ahead and intraday markets that can only be solved instantly using balancing services. An increasing share of VRE generation will create an increasing need for balancing services, which have a cost to the system (Bird et al., 2013).

As an example of this effect, Figure 2-3 show the average frequency restoration reserves (FRR) activations in Germany in 2021, under successive levels of VRE generation. We see a visible upward trend of FRR activation volumes with VRE generation. This effect is also substantiated by other studies, e.g. (Hirth and Ziegenhagen, 2015), (Ortner and Totschnig, 2019), and (Tennet, 2022).

Additionally, compared to conventional thermal units, a high VRE penetration and a lower presence of dispatchable power plants results in a lower inertia in the system, which can generate challenges to the stability of the electricity grid if not proactively managed **(Denholm et al., 2020)**.

Inertia is the ability of a power system to oppose changes in frequency due to resistance provided by the kinetic energy of rotating masses connected to the system. In a system with low inertia, a large sudden power imbalance (for example due to a sudden disconnection of a large production unit) causes a large instantaneous frequency deviation, whereas if there is high inertia in the system, the instantaneous frequency deviation is smaller (FinGrid, 2023). Inertia is thus directly related to the scale of the frequency deviations that must be addressed with balancing services.

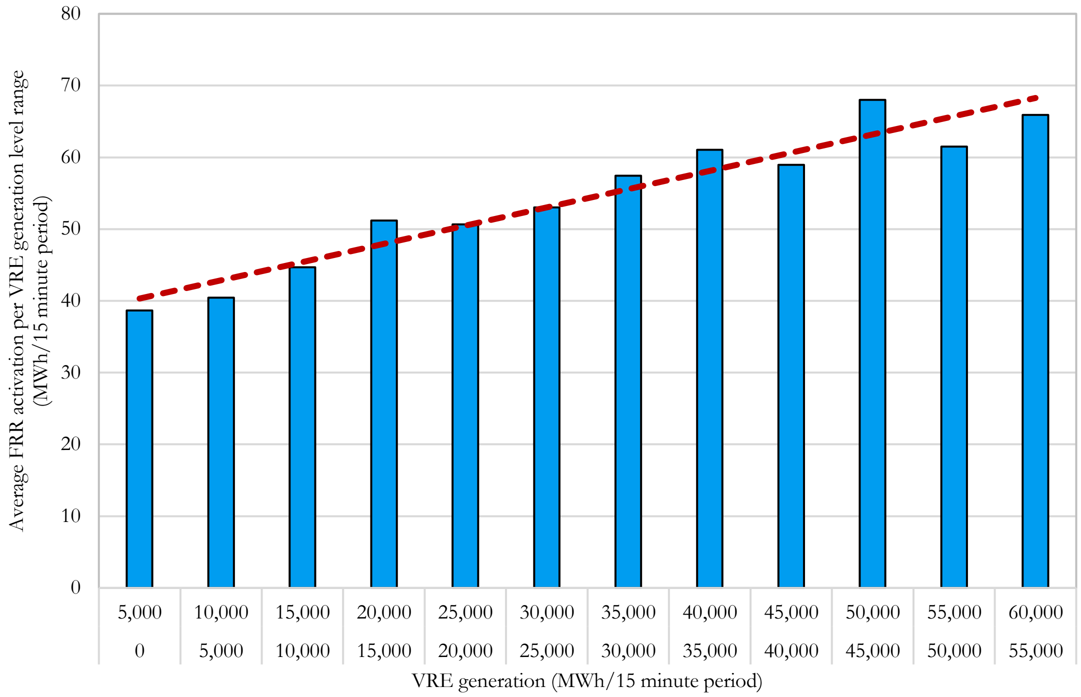

Figure 2-3. Average activation of frequency restoration reserves in Germany in 2021 under increasing VRE generation levels.

Notes: The data has a 15-minute resolution. FRR balancing capacity reserved is in the range of 2 GW for upward and downward aFRR, and 900/700 MW for upward and downward mFRR. However, the actual energy activated is substantially lower as seen in the chart, in the range of 60 MWh per 15-minute period.

Sources: Data for automatic and manual frequency restoration reserves activation in 2021 in Germany from (SMARD, 2022); VRE generation in 2021 in Germany from ENTSO-E Transparency platform (ENTSO-E, 2022a).

2.2.3 Dispatchable generation

Dispatchable generation ensures firm capacity but when based on fossil fuels causes greenhouse gas emissions, energy dependency and price risks.

Traditional flexibility in electricity systems is provided by dispatchable generation responding to price signals that are mostly a result of changes in demand. Hydro power, both reservoir and pumped hydro[8], and fossil-fuel based thermal generation, especially small fast reacting units like gas motors and gas turbines with high ramping capabilities, have historically been the predominant generation-side flexibility elements (Weise, 2021).

While conventional thermal generation dispatchability brings firm capacity and thus a reliable generation source enhancing security of supply, the use of fossil fuels emits greenhouse gases and poses a risk of energy dependence on foreign countries.

As witnessed today, geopolitical turmoil can result in supply stress situations in Europe leading to soaring energy prices and endangering security of supply in Europe. The current energy

[8] Pumped hydro storage systems can be used for both generation and demand (pumping).

emergency situation in Europe has led the EC to propose a series of intervention measures to address high energy prices, including mandatory demand savings and a faster switch from fossil fuels to renewable energy sources (EC, 2022b). Yet, closing the fossil-fuel based dispatchable generation raises the challenge of finding other sources to provide the adequate flexibility in the system.

The penetration of new renewable energy in the electricity system will decrease the number of hours of operation of conventional generation plants which, in the absence of other measures, can impair the system resource adequacy to ensure that demand can be always supplied. The recent proposal on the Electricity Market Design by the European Commission (EC, 2023b) includes recommendations for Member States to design capacity mechanisms that promote flexible, fossil-free technologies that are aligned with the Guidelines on State aid for climate and environmental protection.

2.2.4 Decentralisation

The more decentralised nature of VRE generation increases the role and importance of distribution networks in the overall system planning and operation.

Historically, electricity has been generated at large power plants connected to high voltage (transmission) networks. The electricity is then transported to substations, where it is transformed to lower (usually medium) voltage levels and fed into distribution networks. From there, electricity is distributed and transformed to low voltage before it finally reaches the end consumer. Under this traditional system, Transmission System Operators (TSOs) predominantly rely on centralised, large-scale generators to balance the electricity grid. The role of Distribution System Operators (DSOs) is then to ensure sufficient network capacity to meet consumers demand for electricity generated upstream.

The emergence of smaller scale generation located closer to the point of consumption and often connected to the distribution grids changes the traditional unidirectional paradigm and urges new roles for DSOs, who must become more active system operators, procure flexibility services (voltage regulation or local congestion management) from their network users and coordinate resources with TSOs for the procurement of frequency regulation services (IRENA, 2020).

As such, by 2030, around 50% of VRE could be connected at DSO level across the EU, according to (ENTSO-E, 2019a). At the same time, the development of VRE connected at medium/low voltage levels to distribution grids can increase bottlenecks in the distribution network, requiring additional efforts in grid reinforcements at distribution level (Ahmadi et al., 2022).

2.2.5 Barriers to market entry

Barriers to market entry for new generation is detrimental to a liberalised electricity market, and even more so for a decarbonized and resilient electricity system

With higher VRE supply, energy markets will face higher and more likely price volatilities. Although current price developments in the wake of inflation and the Ukraine war suggest differently, close-to-zero or even low negative prices can become frequent with high VRE shares in generation, while price spikes will exist in hours of low VRE generation. Wholesale markets and products need therefore to adapt to these developments. Eventually, a changing landscape of energy supply has an impact on end-consumers who, by adapting their demand, can also contribute in varying extents to the stability of the system.

ACER monitors the barriers to efficient price formation and the entry of new and small market players (EC, 2019a). Efficient and unbiased price formation is key to ensure that market price signals enable cost-efficient investments. Easy entry for new market players is crucial to attract innovative solutions including new renewable technologies. It also ensures an adequate level of competition, for example by allowing small non-conventional producers to enter the market sometimes still dominated by legacy incumbents. Both efficient prices and the entry of new players are important for lowering the overall societal cost of the green energy transition.

ACER's market monitoring report provides indicators measuring how member states perform against key features that contribute to efficient prices and easy market entry (ACER, 2021a). It provides a list of barriers across member states, whereof four are most relevant for the green energy transition and security of electricity supply:

- **Price limits** in wholesale and retail markets. They can have several designs, such as being fixed or flexible, or set on retail versus wholesale level. Mechanisms requiring generators to offer production at regulated price limits reduce competitive pressure in the wholesale markets, hence affecting liquidity, and innovation. Also at the retail level, subsidised or fixed price contracts can be detrimental to energy savings and efficiency gains, as well as to enable end-consumers to participate more actively in the energy markets, which could facilitate the integration of renewable energy and contribute to system needs. In the context of the 2022 energy crisis, price limit discussions came back on the table.

- **Subsidies** for certain energy sources. The subsidies provided to fossil fuels can be a significant barrier to the deployment of renewables (EC, 2022n). Fossil fuels receive subsidies in the form of e.g. tax reductions, predominantly in the transport sector (EEA, 2023b), which can create distortions to the market, for example, by decelerating the electrification of transport. Furthermore, there are different support schemes for renewable energy in place across the EU. The report on the performance of support for renewable electricity sources states that in many Member States, tenders reduced subsidy costs compared to administrative schemes, enhanced the deployment of renewable capacities and provided a solid framework for technological improvement (EC, 2022c). Some RES support mechanisms are also more efficient than others (e.g., contract-for-difference vs feed-if-tariffs). By such, less distortion in the wholesale markets can be achieved. Competitive procedures can contribute to security of supply through specific tender design elements that introduce additional selection criteria. Yet, tenders including security of supply elements (e.g., hybrid renewable generation and storage projects) are uncommon and could be developed further.

- **Cross-zonal capacities**. Insufficient cross-zonal capacity available for trade will lead to inefficiencies in matching supply and demand, thus limiting welfare and cross-border adequacy support. A larger amount of cross-zonal capacity available for trade increases cross-border competition and allows for a greater integration of renewable energy (ACER, 2021a). EU Regulation on the internal electricity market requires a minimum capacity margin available for cross-zonal trade of at least 70 % by 2025 (EC, 2019b). According to ACER there is still a diverse picture of the levels of margin available for cross-zonal trade across EU with significant room for improvement for most regions and borders in 2021.

- **Market-entry barriers**. Restrictive requirements in prequalification, for example for balancing products, will hamper market entry of smaller assets including small renewable producers (ACER, 2021a). Aggregation of distributed resources can help to overcome such barriers and thus should be promoted.

- **Configuration of bidding zones**. An optimal configuration will decrease the need for frequency congestion in the grid, for corrective measures, and will improve the efficiency of wholesale pricing. Therefore, efforts are made into finding better configurations through the next years. ACER assesses the efficiency of current bidding zone configurations continuously (EC, 2015). If there are inefficiencies in the current bidding zone configuration, ACER can request the relevant Transmission System Operators (TSOs) to launch a review of existing bidding zone configurations (EC, 2015). The right locational market price signals must be in place to drive interconnection investments where they are most needed (highest price differentials observed). The same can be said for generation and demand assets, which can be incentivized to locate in market zones of higher and lower prices. This is of relevance in the design of bidding zones, where a balance must be met between large enough market zones to provide liquidity and avoid market power, and the fit of the market zones to the physical limitations of the grid.

2.2.6 Supply chain and public acceptance

Supply chain risks, public acceptance and system security are challenges the EU electricity system must overcome in its drive to decarbonize.

Many renewable technologies are currently available and cost-competitive across the EU. These developments were possible thanks to rapid technological learning over the past decade, to competitive practices for capacity procurement, such as auctions, being adopted by national regulatory agencies, and to high fossil fuel prices (IRENA, 2022). However, as Member States seek to upscale renewable generation and adjacent infrastructure by 2030 to decarbonise electricity supply, access to raw materials may emerge as a new challenge for European enterprises during this decade (EC, 2022g) (EC, 2021c). For instance, magnets used in wind turbines require rare earths; new electricity grids need copper and electrical batteries for stationary (grid frequency regulation) or mobility applications need access to minerals, such as lithium, nickel, cobalt, manganese, and graphite (IEA, 2021). To understand the potential implications thereof, the EC has set out to assess supply chain risks and their costs for the energy transition, along with necessary measures to mitigate potential disruptions, and will adopt a European Critical Raw Materials Act in 2023 (EC, 2021c).

Another hurdle in the way of an accelerated EU energy transition regards the average length and complexity of permitting procedures. In some Member States, the entire permit-granting process for large renewable energy projects can take up to 9 years (EC, 2022e). To counter the risk of low renewable capacity deployments or even bottlenecks in the next years, the EC has tabled emergency measures for permitting (EC, 2022h) laying down a framework to accelerate the deployment of renewable energy (ACER, 2022a). There are also other targeted amendments on permitting as part of the RepowerEU proposal, now part of the revised REDII (text still to be approved formally by the European Council and the European Parliament). Once formally approved by the Council and the EU Parliament, the measures should promote renewable energy infrastructure deployment and swifter permit-granting procedures for projects of overriding public interest, complementing previous recommendations on best practices in permitting procedures(EC, 2022f) (NEMO Committee, 2023) (ACER, 2023). Alongside, environmental concerns must be considered (flora and fauna in protected habitats, for instance).

Finally, a speedy transformation of the electricity and energy systems will include other challenges such as access to skilled labour to develop renewable projects, and IT security risks in a more digitalised electricity system. To improve the access to skilled labour in renewable projects, renewable energy trade associations and representatives of installers of clean technologies, supported by the EC, have set up a large-scale skills partnership for the renewable energy industrial ecosystem. the EC has recently launched the Pact for Skills (EC-DG ENER, 2023). IT security risks (for instance cyber-attacks), linked with the ubiquitous digitalisation and integration of the energy system, can have potential disruptive effects on the grid and the security of supply. The IT security problem is included in the set of actions to digitalise the energy sector to improve efficiency and renewable integration by the European Commission (EC, 2022j). New legislation will be developed to strengthen the cybersecurity of energy networks, including a Network Code for cybersecurity aspects of cross-border electricity flows under the EU Electricity Regulation and Council Recommendation to improve the resilience of critical infrastructures.

2.3 Solutions

In the pursuit of decarbonizing energy consumption while not compromising security of supply, solutions are needed on the supply and demand side as well as on infrastructure and policy level.

While in the past we had separated vertical energy systems (electricity, heating, gas, oil, etc.), currently we are shifting towards a more integrated energy system, where renewable electricity supply becomes dominant. The new development will be based mainly on wind turbines and solar PV modules, but there are also options to develop hydro power, geothermal energy and other renewable energy sources to a lesser extent. As wind and solar generation are governed by weather conditions and do not follow demand, solutions to address this mismatch at different temporal windows are needed (both for the short term (daily/hourly variation) and the long term (seasonal variation)).

On the demand side, flexibility is needed in the system, so electricity demand can adjust to variable electricity supply, in contrast to the conventional system where dispatchable generation matched a rather inflexible demand. Demand-side solutions include both reduced demand (energy efficiency) to lower the overall generation needs from the supply side, and shift of demand away from peak hours to reduce the need for dispatchable assets (demand shifting). Energy system integration and sector coupling are needed to link the supply and demand components, and infrastructure solutions, including increased transmission capacity, are needed to realise such flexibility and support the decarbonisation of the energy system.

In the sub-chapters below, we highlight how supply-side, demand-side and infrastructure solutions can contribute to the needed flexibility (estimated in section 3.2.2) and support decarbonisation. Each topic is then further detailed in chapter 4 using case studies to highlight real-world applications of innovative solutions. A summary table with a wide range of solutions for the list of challenges that were described earlier in chapter 2.2 (and some additional ones) can be found in Annex 2. The description of the main solutions focusing on flexibility are grouped under supply, demand, infrastructure and market and regulatory aspects.

2.3.1 Supply side flexibility

As discussed in Chapter 2.1, the amount of RES generation must triple over the coming decade, with the largest increases expected to come from VRE, notably solar and wind. Although this is a significant step towards decarbonizing the EU energy systems, it does not solve the question of adequacy, as neither wind nor solar resources will always be available to supply demand.

Today, hydropower from reservoirs is the greatest non-fossil supply-side source for flexibility in Europe, producing around 15-20% of the annual electricity generation in Europe, while pumped hydro storage provides more than 90% of the EU's storage capacity (EC-DG ENER, 2020). Hydropower turbines have high ramping capabilities and can vary their output very flexibly to the system and market needs. The potential for large scale hydropower (above 10 MW) in Europe is largely exploited (EEA, 2018), but new pumped hydro reservoir projects may still be developed where they can be aligned with environmental requirements. Although mentioned in this supply-side section, pumped hydro storage also acts as consumption in the system.

New VRE projects can contribute to a certain degree to the system adequacy. Hybrid plants including energy storage systems and/or combining different renewable technologies (and/or consumption systems such as an electrolyser), can mitigate the variability of their electricity feed to the grid and therefore contribute to system flexibility. Furthermore, different design concepts for VRE projects can also contribute to flexibility in the system (or reducing the flexibility needed by other resources to compensate the demand VRE gap in different time horizons). As highlighted in (EC, 2019h), solar and wind projects can be designed so as their profiles are easier to integrate in the system, for example, with east-west oriented PV panels or advanced wind turbines with larger rotor diameter to capacity ratios enabling them to deliver higher outputs at low wind speeds. These VRE concept designs were coined in (EC, 2019h) as system friendly RES technologies.

Furthermore, the right combination of VRE technologies across geographies can also reduce the generation-demand gap and thus the need for other flexible resources in the system. As it is found in Chapter 3.1, the aggregation of diverse wind and solar resources in Europe can lead to smoother generation outputs and mitigate to a certain extent the inherent volatility of local intermittent resources. The benefits brought by the combination of VRE resources across Europe call for a more interconnected European electricity network.

On the supply-side, the main sources for flexibility until 2030 are still expected to come from dispatchable technologies such as thermal power plants and hydropower (EC, 2021e). Thermal power plants are dominated by fossil fuels, but some renewable based thermal power comes today from biomass (mainly solid biomass, but also biogas and to a very limited extent bioliquids) and geothermal. While hydrogen produced in electrolysis plants could constitute an abundant source for clean gas to be used in gas turbines, challenges to its use concern the efficiency penalty of the power-to-gas-to-power cycle, the availability of renewable power to produce green hydrogen and, to a lesser extent, the technology-readiness of gas turbines that can run on hydrogen (blended with natural gas or only hydrogen)[9].

2.3.2 Demand-side flexibility

Demand-side flexibility is likely to become an important solution in a future electricity system dominated by VRE. As defined in (EU, 2019), demand-side flexibility refers to the change of electricity load by final consumers from their normal or current consumption patterns in response to market signals. This includes response to time-variable electricity prices or incentive payments, or in response to the acceptance of the final customer's bid to sell demand reduction or increase at a price in an organised market, whether alone or through aggregation. (SmartEn, 2021) refers to demand-side flexibility as the deviation to the planned consumption in response to price signals or instruction, on residential, commercial, or industrial sites. As shown in the complementarity analysis developed in chapter 3, demand-side flexibility (especially peak load shaving) has positive effects in balancing supply and demand throughout Europe.

Energy efficiency

Energy efficiency improvements and savings contribute to flexibility provisions in the electricity system, directly and indirectly. The 2030 energy efficiency targets are, in essence, absolute targets on primary and final energy use. To reach them, energy savings will be needed, including during periods of peak energy demand, such as morning and evening hours that coincide with peak VRE deficits (see chapter 3.2). In this regard, the REPowerEU plan clarifies the importance

[9] Solutions for new or upgraded existing gas turbines to run on hydrogen are being developed by technology manufacturers today so they can become commercially viable in the coming years (General Electric, 2023), (Mitsubishi Power, 2022b), (Siemens, 2023).

of ‘immediate energy savings through behavioural changes’ as important near-term opportunity to improve energy system security in response to the energy supply crisis that ensued Russia’s aggression on Ukraine (EC, 2022a).

Energy can be saved in the short term by optimising energy use and reducing wasteful practices, and in the medium and long term by improving the efficiency of buildings and appliances (EEA, 2023a). As such, it becomes easier to decarbonise the economy and improve energy security of supply by 2030, when energy efficiency measures reduce (peak) electricity demand and the necessity for additional generation capacity and flexibility provisions in the system.

Energy efficiency measures focusing on the thermal insulation of buildings are also a key enabler to couple electricity supply and buildings smartly, allowing buildings to actively participate in demand response and load-shifting. The Energy Efficiency First principle (EC, 2021d) must give priority to demand-side resources whenever they are more cost effective from a societal perspective than investments in energy infrastructure in meeting policy objectives (EC, 2021f).

Demand response

Demand response provides cost-effective opportunities in terms of decarbonisation. In general, it can be cheaper and cleaner to reduce or postpone demand, than to activate additional supply. Upscaling such flexibility (from e.g., electric vehicles, electric heating and cooling applications, and the shifting of commercial and industrial loads) is of importance to cost-effectively achieve the EU’s climate mitigation targets for 2030 and beyond. To that end, recently, the EU Commission has proposed the introduction of new support schemes for demand response and storage in its proposal for a reform of the EU electricity market design (EC, 2023c).

As an energy resource, demand side flexibility works by empowering consumers to be at the heart of the solution towards a decarbonised and secure electricity system. Consumers with decentralised energy resources could self-consume their on-site generated renewable electricity, or store and trade any excess or deficit, either directly or through local communities and aggregators (EEA, 2022b). The role of large industrial consumers will also be essential in providing these flexibility services.

To enhance demand-side flexibility, electricity markets and mechanisms are needed to boost demand-side sectors. This includes small scale active consumers and prosumers to activate their flexibility potential based on market signals. Market signals can be *implicit* on retail contract prices and/or network tariffs (implicit demand response) or *explicit* in energy markets where consumers participate (optionally through aggregators) and receive payments in return for availability and activation (explicit demand response).

While in principal electricity markets are open to demand-side response and small consumers, there are still barriers. Among others, these include a fragmented regulatory framework, the lack of market products suitable for small end-users, and the lack of common measurement and quantification methodologies for the demand response services provided (F. D’Ettorre et al., 2022) (EEA, 2022b)[10]. Demand response should have access to all electricity markets on equal footing with any other energy resources, as requested by the EU energy legislation framework (see Regulation (EU) 2019/943, Article 3 (j) (EC, 2022l)). This includes wholesale markets and ancillary service markets.

[10] ACER is also working on an upcoming 2023 study on barriers to demand response.

Although this is the case in most European countries, there are still some countries where ancillary services are restricted to generation resources (Estonia, Greece, Latvia, Romania, within the EU, as well as Serbia and North Macedonia, two EU candidate countries in the EU Neighbourhood initiative in the Western Balkans, according to (ENTSO-E, 2022e)). As analysed in the UVAM case study in chapter 4.4, there are barriers for the participation of decentralised demand response resources through aggregation in ancillary service markets in most countries. These can be a high minimum bid size, undeveloped prequalification procedures, lacking definition of the aggregator role in the national legislation or inexistence of these in the country, etc. (Smart Energy Europe, 2022).

Contribution from active consumers[11]

Active consumers can play a significant role in the energy transition, as well related to secure energy supply. Overall, demand must increase in times of high renewable energy supply, benefitting from lower prices, and decrease in low-availability periods to contribute to adequacy terms. Examples of active consumer engagement in electricity system needs can be found in the Crowdflex project (National Grid ESO, 2021), where domestic demand shifting and flexibility was investigated, or in the project V2Market (V2Market, 2022), which developed an innovative service to incorporate EV batteries into the electricity system as storage and flexibility capacity.

At present, there may be limited incentives for residential customers to participate in demand response schemes, but this is changing. In the future, potential benefits for consumers in reducing costs will substantially increase. Tariffs will adapt appropriately, and new technologies such as smart meters or - someday - remotely adjustable appliances will facilitate further opportunities. What is needed is that consumers should be able to benefit from direct participation in the market, by adjusting their consumption according to market signals and benefiting from lower electricity prices or other incentive payments. Therefore, consumers need easier access to information about possibilities of active participation.

That alone might help incentivising them to participate in certain kinds of demand response. Also, explaining, educating and campaigning can play a key role in increasing the engagement of people as regards their consumption behaviours, e.g., avoiding turning on energy intensive appliances in the evening peak hours, or adapting thermostats to the season. For example, in the context of the current energy crisis in Europe, the decrease in gas consumption in Europe (17.7% between August 2022 and March 2023, compared to the average consumption for the same months between 2017 and 2022 (Eurostat, 2023a)) can be partially attributed to the decrease in gas consumption for heating purposes in buildings as a response to higher energy prices, but also to the campaign on energy savings in Europe and the advice on reducing indoor temperature in winter (Ruhnau et al., 2023).

For less active consumers who will not adjust consumption straightaway, a system-friendly tariff, which partly exist already across member states could, on the one hand, provide price certainty, and on the other hand add time-varying components. Fully enabled active participation will

[11] The Electricity Market Design proposal (EC, 2023c) uses the term 'active customer', which refers to an individual final customer or a group of jointly acting final customers, who consumes or stores electricity generated within its premises located within confined boundaries or self-generated or shared electricity within other premises located within the same bidding zone, or who sells self-generated electricity or participates in flexibility or energy efficiency schemes, provided that those activities do not constitute its primary commercial or professional activity."

require the deployment of smart metering systems and dynamic electricity price contracts. Such systems exist partially in the EU already.

The EU Directive on the internal electricity market (EC, 2019f) requires member states to ensure that final consumers who have a smart meter installed can conclude dynamic electricity price contracts, but the implementation of the clause has not yet taken place across all EU countries. As regards smart meters, data security and interoperability issues are of high concern, as well as undue price risks coming from wholesale markets. The recent Commission Proposal for the revision of the Electricity Market Design (EC, 2023b) includes provisions on the smart meter rollout and the possibility of having submeters associated to specific loads in the house (e.g. EV, heat pump), for which different suppliers can be contracted.

To maximise the benefits and effectiveness of dynamic electricity pricing, the share of fixed components (e.g., tariff for contracted power, regulated charges and other levies) in electricity bills may need to be reduced. At the same time, it should be ensured that consumers contribute adequately to overall system costs. On top of dynamic contracts, customers can contribute to the electricity market by trading available flexibility or even self-generated electricity on an aggregated level. Customers should be able to make full use of the advantages of aggregation (EC, 2019d).

2.3.3 Infrastructure solutions and decentralisation

Cross-border transmission helps share VRE resources and reduces domestic flexibility needs

The EU strives for an integrated electricity market to maximise socioeconomic welfare of all EU actors. The internal European electricity market[12] is set to bring substantial efficiency gains compared to isolated national electricity markets. The market mechanism that enables the single European electricity market are the single day-ahead and intraday coupling (SDAC and SIDC respectively), together with balancing market mechanisms allowing the cross-border coordination of these services[13] and the trading of transmission rights in forward capacity allocation.

Transmission capacity between countries represents the enabler of physical cross-border trade for the EU electricity market integration, with an interconnection target of at least 15% (of national generation capacities) being set for each country for 2030. In 2021, 16 countries reported being on track or having reached that target, but more interconnections are needed in some regions (EC, 2023a).

Moreover, the Electricity Regulation 2019/943 (EC, 2019b)[14] requires TSOs to ensure that at least 70% of the transmission capacity is offered for cross-zonal trade, while respecting operational security limits. In 2022, ACER concluded that interconnectivity has remained fairly unchanged since 2020 and does not meet the 70% target at all times, significant room being available to improve cross-zonal trading (ACER, 2022b). The minimum 70% target is also relevant for the identification of alternative bidding zone configurations. The minimum target has become a key element of market integration, which requires monitoring.

[12] Short description of its historical development available in (European Parliament, 2022).

[13] See these cross-border mechanisms for balancing services in (ENTSO-E, 2021b)

[14] Article 16(8) of the Electricity Regulation of the Clean Energy Package (EC, 2019f)

Bidding zone configurations determine the interaction of demand and supply, and thus impact renewable energy development as well as investments into generation capacities. There are three objectives for scaling bidding zones optimally: maximisation of economic efficiency, maximisation of cross-zonal trading opportunities, and the level of security of supply. Currently however, bidding zones in Europe are mostly defined by national borders, rather than by actual network congestions. Hence, alternative bidding zone configurations need to be examined. However, it is not only lack of cross-zonal interconnection capacities which prevents cross-border trade, but also internal congestions, which need to be tackled. ACER recently published its bidding zone review decision (ACER, 2022a).

For increasing electricity market integration, sustainability, and security of supply, EU legislations (e.g., Electricity Regulation 2019/943) currently aim to better link the energy infrastructure of EU countries. ENTSO-E's biennial ten-year network development plan (TYNDP) identifies investment gaps and evaluates the benefits of individual projects against different future scenarios. The regulation for the trans-European networks for energy (TEN-E) sets priority corridors and projects and facilitates their implementation via faster permit granting and use of enhanced regulatory tools. The TEN-E regulation was revised recently so as to better emphasise sea-basin based offshore wind development plans (EC, 2022d). EU funding for energy infrastructure can be provided under the scheme of Connecting Europe Facility (CEF) for projects of common interest (PCI).

As an example of cross-zonal infrastructure, one of the priority corridors is known as the North Seas Offshore Grid (NSOG). This PCI connects several offshore wind platforms to several Member States. It does not only connect grids in the North Sea to transport electricity from offshore wind sources to centres of consumption and storage, but also increases cross-border electricity exchange (ENTSO-E, 2022c).

Distributed electricity systems can provide additional benefits in integrating renewable generation

Supported by ICT and AI developments, distributed electricity systems are an enabler for renewable integration in local grids and a solution to enhance the use of small flexibility sources (like household heat pumps or batteries), for a more efficient exploitation of local energy resources and operation of distribution system networks.

A distributed electricity system is a system in which smaller generation facilities are installed at closer proximity to consumers, which contrasts with a central electricity system, where large power plants are located further away from consumers. By closing the gap between production and consumption with the use of microgrids, the goal to better utilise renewable generation, reduce fossil fuel use and enhance grid resilience (NAS, 2023)*. The local integration of electricity, heating and transportation systems is an important option to increase flexibility, such systems normally including distributed generation, energy storage (small-scale batteries) and controllable loads, such as electric vehicles, heat pumps or other demand response.*

Distributed energy resources will shape the energy market in the mid-term, the Italian TSO TERNA's UVAM project (see Chapter 4.4) being already one example that showcases how smaller assets can be made eligible to participate in certain markets to fostering competition.

Conventional centralised electricity systems need transmission and distribution infrastructure to combine supply and demand at large. At this large scale, curtailments are more likely, as infrastructure cannot serve all needs to transport electricity generated from e.g., offshore wind to remote areas of demand (Power-to-X is envisaged to solve this issue). Distributed electricity systems may include energy storage assets, as well as smart appliances (smart meters, smart grids).

2.3.4 Policy and market framework

In 2022, the European wholesale electricity market design has been put to a test in terms of sustainability, affordability, and security of supply, in the wake of the energy crisis. Ahead of the winter 2022-2023, gas and electricity prices reached record heights, taking a toll on European households and industry. This has led to a situation where short-term security of supply considerations partially overruled decarbonisation goals in a few countries, where short-term measures to mitigate immediate risks linked to the energy crisis appeared necessary (see e.g., bringing several coal-fired power stations back to the grid in Germany). Despite such measures, total EU CO_2 emissions were 4% down in the fourth quarter of 2022, compared with the same quarter of 2021, having decreased in all economy sectors except for transport, services and mining (Eurostat, 2023c). The current political situation creates challenges but also opportunities to have a better look on how the EU's goal of decarbonising the energy system and eliminating adequacy concerns can be achieved.

Short-term electricity markets

The need to decarbonise the EU electricity market implies a significant penetration of VRE combined with flexible generation technologies and demand-side response. Due to the inherent volatility of VRE production and the associated uncertainties, intraday (and balancing) markets will need to adapt to rapidly changing weather conditions. Also, close to real time markets must remain highly integrated across borders to ensure flexible and competitive flows of electricity.

The optimal way to unlock the potential of renewable electricity sources is through short-term wholesale electricity markets, such as day-ahead or even intraday markets. Short-term markets do not only bring additional economic opportunity to renewable energy suppliers, but also further reliability support and competition. Short-term trading helps integrate wind and solar and react to volatile price signals more efficiently.

As of today, short-term electricity markets across the EU provide high competition and liquidity levels (ACER, 2022a). Further market integration will improve liquidity and competition, for instance through larger cross-zonal capacities. The better integrated a market and interdependent the bidding zones, the higher the liquidity and the better the combination of demand and supply. Furthermore, interconnections and better utilisation of cross-border capacities will help temper volatilities of renewable energy generation across the system, as shown in the analysis developed in chapter 3. The capacity allocation and congestion management (CACM) regulation, for instance, provides binding rules for the implementation and operation of the EU-wide single market coupling in the day-ahead and intraday timeframes. It applies to the transmission system operators, nominated electricity market operators and regulatory authorities, and sets out minimum harmonised rules for the day-ahead and intraday market coupling, promoting EU-wide and efficient trade in electricity, allowing for flexibility through resource sharing across borders, and better integration of renewables.

CACM 2.0 will further remove barriers for market entry and aims at reducing transaction costs in electricity trading (ACER, 2021b). In general, shorter-term products, as well as intraday auctions, and closure gates closer to real time (letting products be traded shortly before delivery) are key factors for more flexibility, renewables integration and reliability.

The Electricity Regulation imposed new requirements for cross-zonal electricity capacities being offered for cross-zonal trade (EC, 2019f). ACER's monitoring results show that for some bidding zones little progress has been achieved so far (ACER, 2022h). This refers to expansion of cross-border capacities, but also to a more efficient use of available capacities. There are basically two issues related to cross-border interconnector capacity – availability and use – both must increase.

Long-term electricity markets

Long-term electricity markets (or forward markets) are key to hedging opportunities, and thus investment security and adequacy considerations. Throughout the EU, the lack of liquidity in forward markets hampers an efficient use of hedging. This lack of liquidity directly impacts the hedging opportunities of market participants, and eventually influences investment decisions negatively. So far, only the German bidding zone has proven to provide sufficient liquidity in its electricity forward market for forward products covering up to three years to delivery (ACER-CEER, 2023). In most countries, forward markets are not liquid, short-term markets being the preferred or only available option for large consumers, with the risk that supplier's default or cannot adequately maintain their delivery duties during a crisis, as in 2022.

Long-term markets and improved hedging instruments need attention, first, to drive the massive investment needed for the green energy transition (Browning, 2021), and second, so final consumers can benefit from more predictable price signals related to long term average generation costs, instead of being exposed to short-term market prices related to short-run marginal costs of thermal power plants that tend to clear the day-ahead market.

The recent Commission Proposal for the Revision of the Electricity Market Design (EC, 2023b) addresses the issue of liquidity in forward markets with the creation of regional virtual hubs. These regional virtual hubs, by providing a reference price index, should enable the pooling of liquidity and provide better hedging opportunities to market participants. Also, long-term transmission rights should be issued with frequent maturities (ranging from month ahead to at least three years ahead), to be aligned with the typical hedging time horizon of market participants.

Power purchase agreements (PPA)

A Power Purchase Agreement (PPA) is a bilateral agreement between a and a seller of renewable electricity (normally a renewable energy developer) at an agreed price and duration (between 5 to 20 years) hedging the price on both sides.

Besides long-term trading via future markets, PPAs can be used as hedging tool. PPAs can be seen as filling the gap of currently non-functioning forward markets beyond three years ahead, where hedging interest exists on both sides, while organised markets have not developed properly yet (due to e.g. insufficient supply and demand, inadequate market design, high hedging costs) (ACER-CEER, 2023). With a PPA, both a supplier and buyer can hedge against volatile electricity market prices. Both sides benefit from price certainty and can therefore plan the future in terms of return of investments or electricity supply. Insofar, these helps achieve the twin objectives of sustainability and security of supply. However, downsides exist – PPAs can themselves withdraw liquidity in the forward markets. The new electricity market design proposal however expects Member States to facilitate PPAs to reach decarbonisation goals by de-risking and thus incentivising investment in renewable energy while locking low and stable electricity prices over the long-term for consumers.

In 2022, the Commission published a recommendation to facilitate PPAs in order to speed the deployment of renewable energy projects (EC, 2022f). In 2023, the recent EC Proposal for the Revision of the Electricity Market Design (EC, 2023b) also emphasizes the role of PPAs as a long-term hedging instrument and hence includes provisions to reduce the current barriers to access these contracts, such as State-backed guarantee schemes to reduce the offtakers' credit risk and open the PPA market to new and smaller players.

Contract for Difference (CfD)

A Contract for Difference (CfD) is a financial agreement between a generator of renewable energy and a counterparty, often a government or utility company. The CfD guarantees a fixed price for the electricity generated by the renewable energy project over a specified period. Under a CfD contract, if the market price of electricity is lower than the agreed-upon strike price, the counterparty pays the generator the difference to ensure a stable revenue stream. Conversely, if the market price exceeds the strike price, the generator pays the difference back to the counterparty.

The electricity market design reform proposal (EC, 2023b) brings forward CfDs in the light of the expected expansion of renewable generation and for protecting final consumers. To that end, the proposal seeks to make CfDs compulsory for new public support to RES generation. Like PPAs, CfDs can provide price certainty in the long term for investors and consumers, but they also come with risks. On the downside, CfDs may have a negative impact on short-term markets, as they can provide inefficient dispatch incentives by continuous operation at low prices. They may as well reduce the liquidity of forward markets (once a n actor has hedged a CfD with the government, the actor does not need to enter other long-term contracts available in forward markets).

On the other hand, CfDs can provide an effective protection of consumers against high prices, if positive and negative differences are channelled back to consumers. They can also be an effective way to support investments in new renewable generation capacities, as they provide price stability and investment certainty. They may even provide effective means to achieve decarbonisation targets with more certainty and predictability for RES investors than via market operation alone (EC, 2023b).

Capacity mechanisms

Capacity mechanisms are administrative measures aimed at addressing adequacy issues at a broader level. Capacity mechanisms can ensure investments in flexible capacities in case the markets will not suffice (quickly) as incentive driver. Capacity mechanisms can however have a distortive impact on the energy markets, as they influence price bidding behaviours. The EU

Regulation on the internal electricity market insofar defines high-level design principles for capacity mechanisms (EC, 2019b).

To reduce market-distortive effects, capacity mechanisms must be designed to address the specific nature and magnitude of the individual adequacy concern, include competitive procurement processes, and not lead to over-procurement or over-compensation. They are intended only as a temporary measure. To some extent, capacity mechanisms are also open to renewable integration and demand-side response, although certain requirements in national laws may currently hinder the entry and participation of actors able to provide such options (EC, 2023b).

Currently, more than two thirds of the capacity payments in the EU are directed to traditional thermal generation capacity, with long-term capacity contracts, with an annual average value of more than one billion Euro, supporting coal- and natural gas-fuelled generation capacity (ACER, 2022j). This practice hampers the energy transition and the EU carbon-neutrality targets through a systemic bias in favour of dispatchable generation for the provision of system adequacy. A similar bias is also present in the methodology of ENTSO-E within the 2021 European Resource Adequacy Assessment (ERAA) (ENTSO-E, 2021d), where the value of demand-side response was not sufficiently recognized, according to an ACER evaluation (ACER, 2022f). The recent EC Electricity Market Design reform proposal also includes provisions regarding the design or redesign of capacity mechanisms to promote the participation of non-fossil flexibility, such as demand-side response and storage(EC, 2023b).

3 Wind and solar complementarity

We have developed two quantitative analyses based on historical hourly VRE generation and demand, as well as projected VRE generation and demand profiles in 2030 based on the Policy scenarios for delivering the European Green Deal (EC, 2021e).

The first analysis (3.1) aims to quantitatively assess how the aggregation of various VRE technologies and geographies can bring complementarity effects in supplying a more stable generation, better match demand profiles, integrate renewables in the system and support security of supply (by increasing the minimum available level of aggregated VRE generation than for individual technologies or countries).

The second analysis (3.2) seeks to quantitatively evaluate residual demand in Europe. It first addresses residual demand as VRE deficit and excess, looking at peak situations (extreme VRE deficit or excess hours) and overall annual VRE deficit and excess in Europe. Then, we attempt to quantify flexibility needs using the residual demand variation as a metric following the methodology from (EC, 2019g).

In both analyses, complementarity shall be understood as a lower variability[15] of VRE generation profiles, a better correlation to demand, a negative correlation between VRE generation profiles, or a higher minimum available VRE generation.

3.1 Technological and geographical complementarity

The diversity of renewable resources in Europe can be exploited through a well interconnected European electricity grid and market arrangements to enhance any potential complementarities between the different renewable resource types and geographies towards increasing renewable integration and security of electricity supply.

We examine two potential complementarity effects: the complementarity brought by aggregating different VRE technologies (technology complementarity between wind and solar) and the complementarity caused by aggregating VRE generation from different countries in Europe (geographical complementarity). The underlying rationale for this analysis is that the differences between various VRE technology generation profiles (differences in solar and wind-driven energy yields in time) and the differences in energy yields by territory across Europe can complement each other to ensure a more efficient use of the overall installed VRE capacity.

The analysis is based on historical hourly generation and demand time series in the period 2015-2021 from (ENTSO-E, 2022d) for European countries with EEA relevance. These are Belgium, Bulgaria, Czechia, Denmark, Germany, Estonia, Ireland, Greece, Spain, France, Croatia, Italy, Latvia, Lithuania, Luxembourg, Hungary, Netherlands, Austria, Poland, Portugal, Romania, Slovenia, Slovakia, Finland, Sweden, United Kingdom, Norway, Switzerland, Montenegro, North

[15] Variability is either measured by the standard deviation or the coefficient of variation of the timeseries analysed.

Macedonia, Albania, Serbia, Bosnia and Herzegovina, and Kosovo[16]. A summary of complementarity effects identified in this report can be found in Table 3-1.

Table 3-1: Complementarity effects

Complementarity type	Impact	Measure	Implication
Wind – solar technological	Reduces short-term generation variability[17]	-9% vs. onshore wind -16% vs. solar -28% vs. offshore wind	Reduces short-term flexibility needs e.g.: CCGT, battery, DSR.
	Reduces seasonal swing[18]	Coefficient of correlation for solar and wind monthly generation of -0.85	Reduces long-term flexibility needs e.g.: CCGT, long-term storage.
	Better alignment with demand fluctuation[19]	x1.3 vs. onshore wind x2 vs. solar x2.1 vs. offshore wind	Reduces need for demand side response (or other flexibility resources to close the gap between VRE and demand).
Wind - wind[20] geographical	Reduces short-term generation variability[21]	-19% Europe vs. individual countries	Reduces short-term flexibility needs e.g.: CCGT, battery, DSR.
	Maximises minimum availability of VRE resources	At all times, across Europe, at least 8% of the installed VRE is available vs. 0% for individual countries	Positive effect on energy security. Reduces the need for controllable capacity.
Wind - solar geographical	Reduces short-term generation variability	-23% Europe vs. individual countries	Reduces short-term flexibility needs e.g.: CCGT, battery, DSR.
	Maximises minimum availability of VRE resources	No Dunkelflaute[22] events in all Europe. They are always localised events in certain regions.	Mitigate Dunkelflaute events.

[16] This designation is without prejudice to positions on status and is in line with UNSCR 1244/99 and the ICJ Opinion on the Kosovo Declaration of Independence.
The years analysed are 2015 to 2021 and a projection of 2030.

[17] We measure variability by the average standard deviation of hourly timeseries for aggregated VRE (wind + solar) and for individual technologies in European countries from 2015 to 2021. On average for the analysed period, the standard deviation is 21% of the maximum annual generation for aggregated VRE, while this is 23% for onshore wind, 29% for offshore wind, and 25% for solar. The standard deviation measures how much the hourly measurements differ from the annual mean value. It expresses how variable or volatile the hourly profile is.

[18] The average coefficient of correlation of monthly solar and wind generation in European countries from 2015 to 2021 is -0.85. The coefficient of correlation can take values from -1 to 1, where -1 indicates a perfect negative correlation, +1 indicates a perfect positive correlation and 0 indicates no correlation.

[19] The average coefficient of correlation between hourly VRE generation and demand in European countries from 2015 to 2021 is 0.34, while for the individual technology profiles it is lower: 0.27 for onshore wind, 0.16 for offshore wind and 0.17 for solar. Although higher, a correlation of 0.34 is still weak.

[20] Please note that in our analysis we have not found any evidence of geographical complementarity between solar resources due to the high correlation between solar profiles in Europe (average coefficient of correlation of 0.8) since most European Member States are in the same time zone GMT+1. Clouding, etc. does not show substantial evidence for solar complementarity between regions to be highlighted in this work, therefore the solar-solar category cannot be found in the table.

[21] On average in the period 2015-2021, aggregated European VRE generation shows a standard deviation of 0.17% of the maximum hourly generation, while the average standard deviation for individual countries' VRE generation is 0.21%.

[22] Defined in this work as periods when wind and solar generation present a capacity factor (electricity generation / theoretical maximum as per rated power) below 20% for at least 24 successive hours.

Figure 3-1 shows a graphical representation of the complementarity effects identified in the analysis including a decrease in the variability of the VRE generation profile, a better correlation of VRE generation to demand, and a higher minimum generation.

The technological complementarity (the combination of wind and solar technologies) results in lower variability, especially on a seasonal level (higher wind and lower solar in winter; lower wind and higher solar in summer), and a somewhat better correlation to demand (although the correlation is weak). Consequently, exploiting the complementarity of wind and solar can reduce the need for flexibility resources in the system that may need to back up the variability of VRE and cover its unmatching to demand.

The geographical complementarity of wind and solar across different European geographies also results in higher minimum available generation at any hour than for any individual country. This also relates to the inexistence of dark doldrums (Dunkelflaute) events all over Europe. An interconnected electricity system across Europe can benefit from the geographical differences in renewable energy yields and thus there is an overall lower need for additional resources to supply demand. In the case of Dunkelflaute events, countries who experience such events (especially in Northern Europe during winter) can in theory rely on imports from other countries where there is wind and/or solar available generation. Other more local types of generation and flexibility will however likely still be required in these situations.

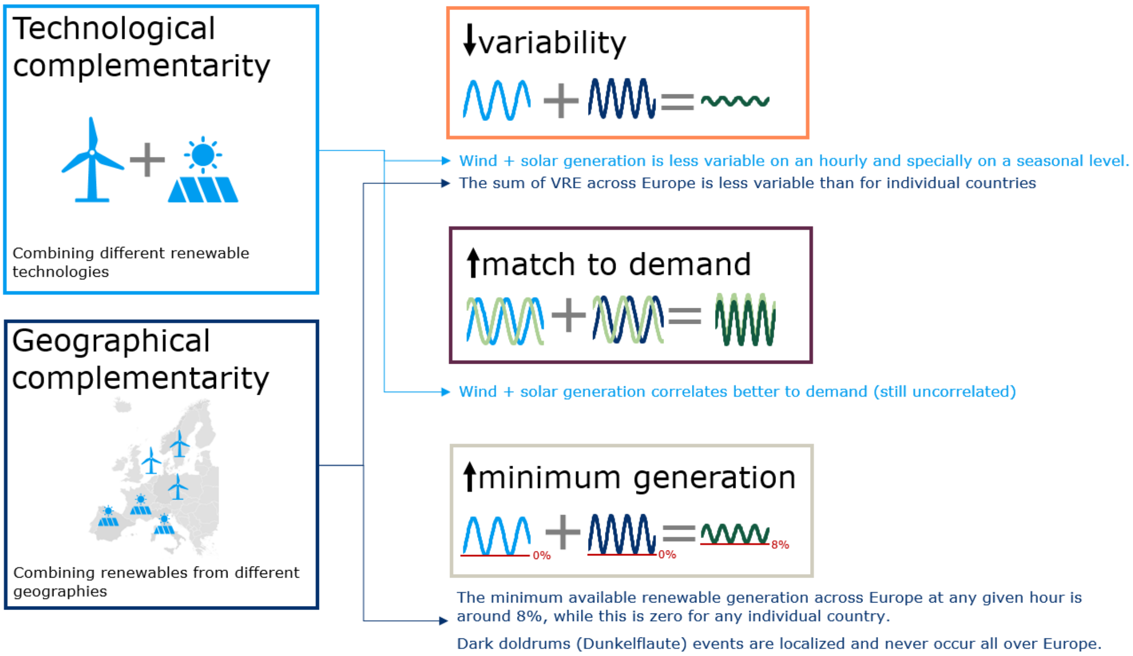

Figure 3-1. Graphical representation of the technological and geographical complementarity effects.

3.1.1 Technological complementarity of wind and solar generation

The combination of wind and solar generation shows lower variability and higher correlation to demand than both technologies taken separately, which can potentially mean lower needs for flexible resources to cover the gap between VRE variability and demand.

A recent analysis highlighted seasonal complementarity, yet it concluded that it was not significant for daily and hourly observations (Jurasz et al., 2021). The same study did highlight a smoother availability pattern in the joint operation of wind and solar and a reduction in the probability of VRE resource droughts when combining wind and solar in hybrid systems. Nonetheless, this study finds that the combination of wind and solar resources in Europe can drive complementary effects. The hourly VRE generation profile resulting from the combination of wind and solar individual generation profiles shows a lower variability: 9% lower than onshore wind, 16% than solar and 28% lower than offshore wind.

We use the standard deviation of hourly generation timeseries as the statistical metric to measure variability. The standard deviation measures how much the hourly measurements differ from the annual mean value. Thus, it expresses how variable or volatile the hourly profile is. Figure 3-2 shows how the combined VRE hourly profile has a lower standard deviation than any individual VRE hourly profile in all years of the period analysed. For aggregated wind and solar generation, the standard deviation is on average 21% of the maximum annual generation, while it is 23% for onshore wind, 29% for offshore wind, and 25% for solar.

The lower variability is explained by combining generation profiles with different peaks and valley times, which net each other to some degree and result in a more stable combined generation. The lower variability of combined wind and solar resources points at a more stable generation output and hence potentially, to a lower need of flexibility resources to cover that variability, albeit that variability levels are still present – the production will not be flat.

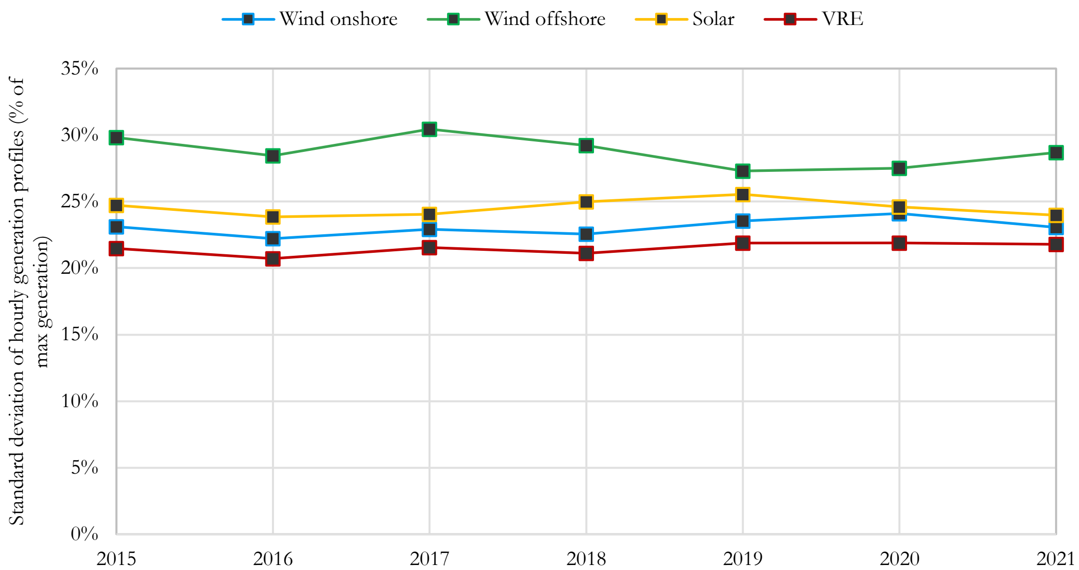

Figure 3-2. Variability of individual and combined VRE generation in Europe measured by the standard deviation of their hourly profiles.

Sources: Hourly generation data from ENTSO-E's transparency platform **(ENTSO-E, 2022d)**.

Notes: VRE refers to wind + solar generation. The values displayed refer to aggregated generation for all European countries with EEA relevance and years analysed.

Combined wind and solar generation profiles present a higher correlation to demand than individual VRE resources: 1.3 times higher than for onshore wind, 2 times higher than for solar, and 2.1 times higher than for offshore wind.

We have used the coefficient of correlation to measure the correlation between VRE generation and demand. The coefficient of correlation can take values from -1 to 1, where -1 indicates a perfect negative correlation, +1 indicates a perfect positive correlation and 0 indicates no correlation. As it can be observed in the left chart in Figure 3-3, all correlation coefficients are below 0.4, which is a weak correlation in all cases. Yet, the improvement when combining wind and solar generation is consistent in all years analysed and signals a potential benefit of combining renewable technologies to fit demand on an hourly basis.

The higher correlation to demand (for hourly timeseries) may be intuitively explained if we examine the hourly profiles for individual and combined VRE generation and demand on an average day. As it can be observed on the right chart on Figure 3-3, the combined shape of wind and solar (red curve) matches better demand, as it includes an inverted U shape like demand but not as steep as the solar profile thanks to the wind generation during night hours.

The higher correlation to demand points to a potential reduction of flexibility needs to cover the gap between demand and VRE generation when wind and solar resources are combined.

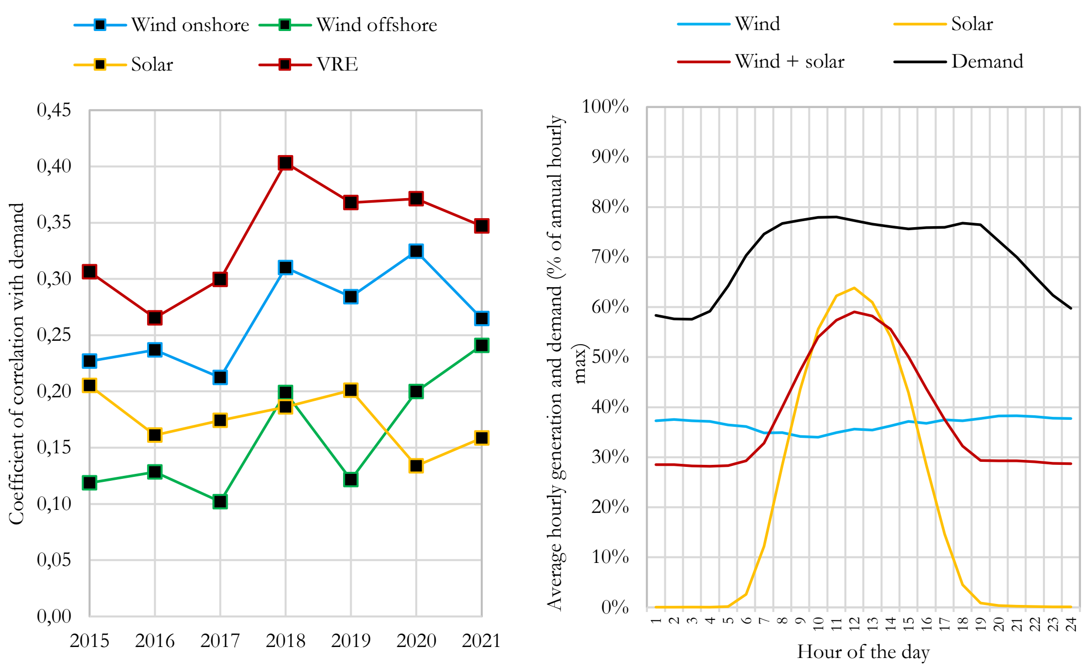

Figure 3-3. Correlation between VRE generation and demand.

Sources: Hourly generation and demand data from ENTSO-E's transparency platform **(ENTSO-E, 2022d)**

Notes: Left: coefficient of correlation of European aggregated VRE individual and combined generation profiles with demand; right: Average hourly European aggregated VRE individual and combined generation and demand profiles in 2021.

In terms of decarbonisation and adequacy, the more VRE available, the better – irrespective of whichever technology (neglecting questionable sources of technical components at this point).

The right combination of VRE resources in the sense of optimal complementarity effects however depends on actual demand patterns, and is subject to natural constraints (wind availability, hours of sunlight), as well as to installation limits such as access to the sea, development costs, etc. Yet, potential VRE technology complementarity effects should not be neglected in European and national energy and climate plans.

The high seasonal complementarity between wind and solar can decrease the needs for seasonal flexibility resources.

We have analysed the complementarity between wind and solar profiles by their correlation level. In the next step we will show that the seasonal complementarity between wind and solar generation is stronger than their complementarity on an hourly basis. Wind power reaches maximum levels in winter (when solar is lower) and solar generation during summer (when wind is lower).

Figure 3-4 shows correlation coefficients between wind and solar on hourly and monthly basis for the European countries analysed. All coefficients are negative for both hourly and monthly generation, indicating an inverse correlation between wind and solar. When one is high, the other tends to be low. While hourly wind and solar generation have negative but low correlation (values ranging from -0.07 to -0.24, with an average of -0.15), monthly wind and solar generation have a stronger negative correlation (in the range from -0.43 to -0.84, with an average of -0.69). For the EU countries Croatia, Netherlands, Germany, France and Belgium, the monthly correlation is below -0.75, which is quite significant. For the hourly correlation, at least Portugal and Sweden reach a level below -0.2.

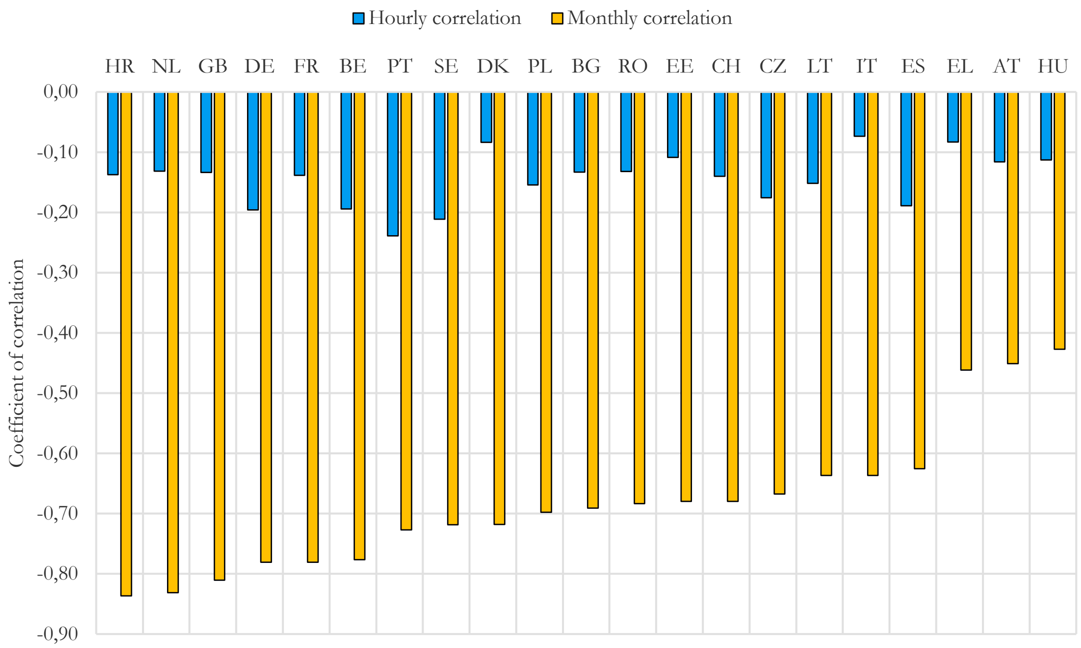

Figure 3-4. Correlation between wind and solar generation.

Sources: Hourly generation data from ENTSO-E's transparency platform **(ENTSO-E, 2022d)**

Notes: Average coefficient of correlation between wind and solar on hourly and monthly basis in the period 2015-2021 for the European countries analysed, with complete hourly data available for wind and solar generation.

The seasonal complementarity between wind and solar can also be observed on Figure 3-5, where the aggregation of monthly wind and solar VRE sources results in a more stable profile than any individual VRE source.

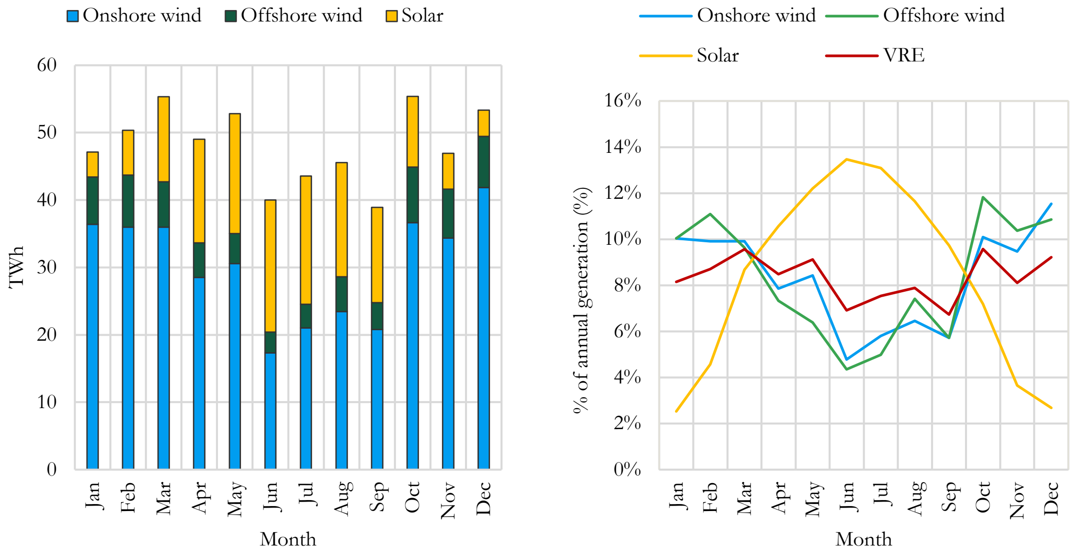

Figure 3-5. Monthly wind and solar VRE generation in Europe in 2021.

Sources: Hourly generation data from ENTSO-E's transparency platform **(ENTSO-E, 2022d)**

Notes: Left: monthly VRE generation in Europe in 2021 by VRE source; right: distribution of VRE generation by month in Europe in 2021.

The negative correlation of wind and solar, especially on an hourly basis, prevents simultaneous peaks of high or low generation from both sources, which can relieve the need for peak flexibility resources.

The negative correlation between wind and solar is also mirrored in the absence of simultaneous events of very high or very low generation. Few exceptions apply. Events of very low simultaneous generation from wind and solar are related to Dunkelflaute events, which are also characterised for being persistent for successive hours. These events are analysed in more detail in section 3.1.3.

Wind and solar peaks (high generation) and valleys (low generation) rarely occur at the same time. Figure 3-6 can help quantify this. It shows the percentage of annual daylight hours[23] when both wind and solar are above (left chart) or below (right chart) specific output levels (measured as percentage of the annual maximum hourly generation) in the European countries analysed in this work. For example, while wind generation alone is above 70% in 8% of the daylight hours in the year (blue curve, left chart), and solar is above 70% in 10% of the hours, both wind and solar are simultaneously above 70% in 0.3% of the hours (red curve, left chart). Same goes for coinciding low wind and solar generation. While wind alone is below 5% in 12% of the daylight hours (blue curve, right chart) and solar alone is below 5% in 32% of the hours, combined wind and solar are below 5% in only 3% of the hours.

[23] All hours with solar generation below 0.01% are considered as night hours and not counted.

This non simultaneity of high or low wind and solar generation is of value in reducing VRE excess or deficit situations in the system compared to systems where only wind or solar generation are developed and not a combination of the two. Systems with wind and solar can thus require less flexibility resources than systems with only one of the two. This is another complementary effect that should not be neglected when defining technology-specific renewable targets in national energy and climate plans.

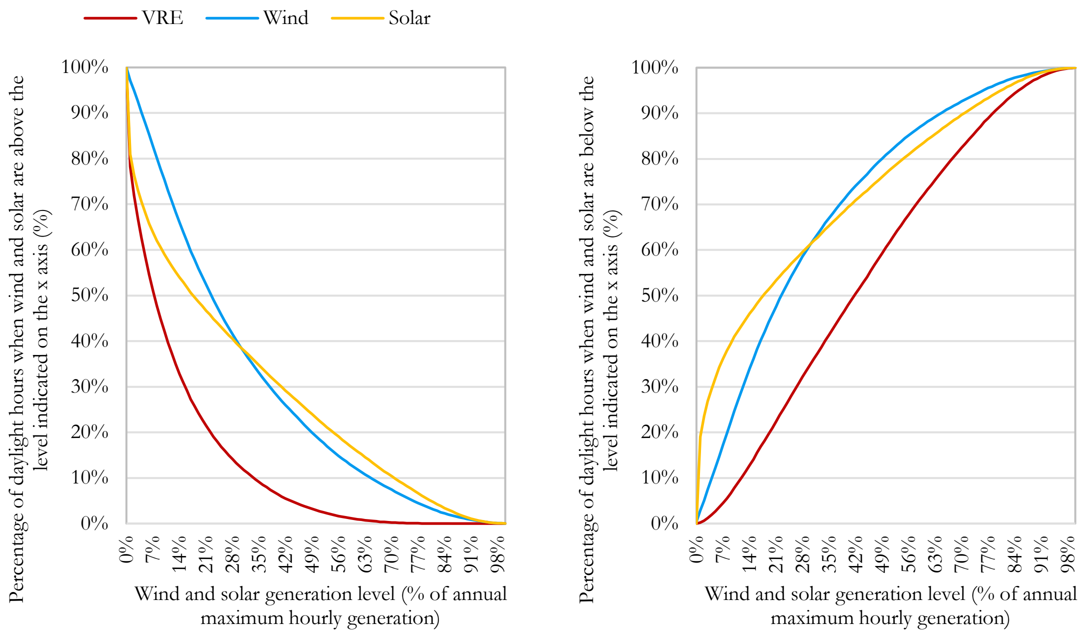

Figure 3-6. Simultaneous wind and solar generation above (left chart) and below (right chart) the levels indicated on the x axis.

Sources: Hourly generation data from ENTSO-E's transparency platform **(ENTSO-E, 2022d)**

Notes: Percentage of daylight hours when wind and solar are above (left chart) or below (right chart) the level indicated on the x axis. Red curve: combined generation; blue curve: wind generation; yellow curve: solar generation. The analysis has been done over hourly generation for the European countries with EEA relevance with complete data available for hourly wind and solar generation in 2021. Note that the curves are not symmetrical because of the simultaneity condition on each individual wind and solar generation profile.

3.1.2 Geographical complementarity of wind resources

The general uncorrelation of wind profiles across Europe can favour geographical complementarity effects and reduce flexibility needs.

Wind patterns vary across Europe and these differences are observed to be higher the further the countries are apart. In general, neighbouring countries present similar wind generation profiles and thus a high coefficient of correlation between wind generation time series. Complementarity effects (measured as a lower variability of aggregated profiles) can therefore be exploited between uncorrelated wind profiles from non-neighbouring countries. At first, we focus on wind only, as capacities are much higher throughout Europe than the PV's shares, and as we want to assess the geographical complementarity potential explicitly, without technological complementarity effects. Solar PV is analysed in chapter 3.1.3.

Correlation of wind between the European countries analysed in this work decreases with distance as it can be observed in Figure 3-7. It refers to both on- and offshore wind. The lower the correlation, the better the complementarity effects. Assuming unlimited cross-border interconnection capacities (and absence of bottlenecks within a country), complementarity across Europe is visible.

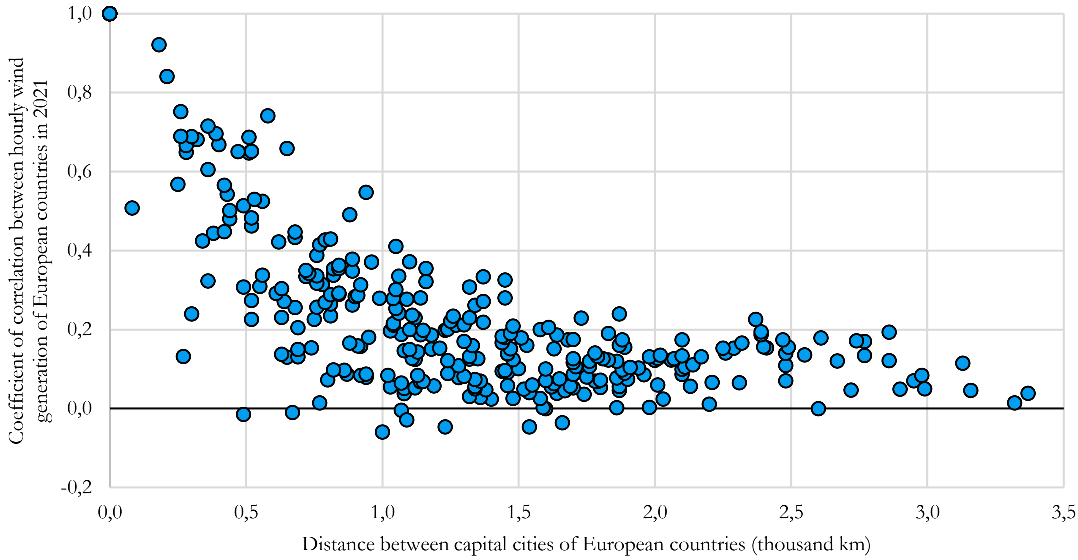

Figure 3-7. Wind correlation and distance between European countries with EEA relevance.

Sources: Hourly generation data from ENTSOE transparency platform **(ENTSO-E, 2022d)**

Wind correlation coefficient values range from -0.1 to 0.9, meaning that wind profiles tend to not correlate or correlate positively (when wind is high in country A, it tends to be high in country B as well). The bigger the distance between countries, the better the complementarity. A few exceptions apply though: there is even negative correlation recognizable for the sample year 2021 in the case of countries which are not that far away from each other. Negative correlated wind profiles (high wind in country A, low wind in country B) provide the highest complementarity potential. There are only a few and very low negative wind correlation samples however observed between the European countries analysed in this work.

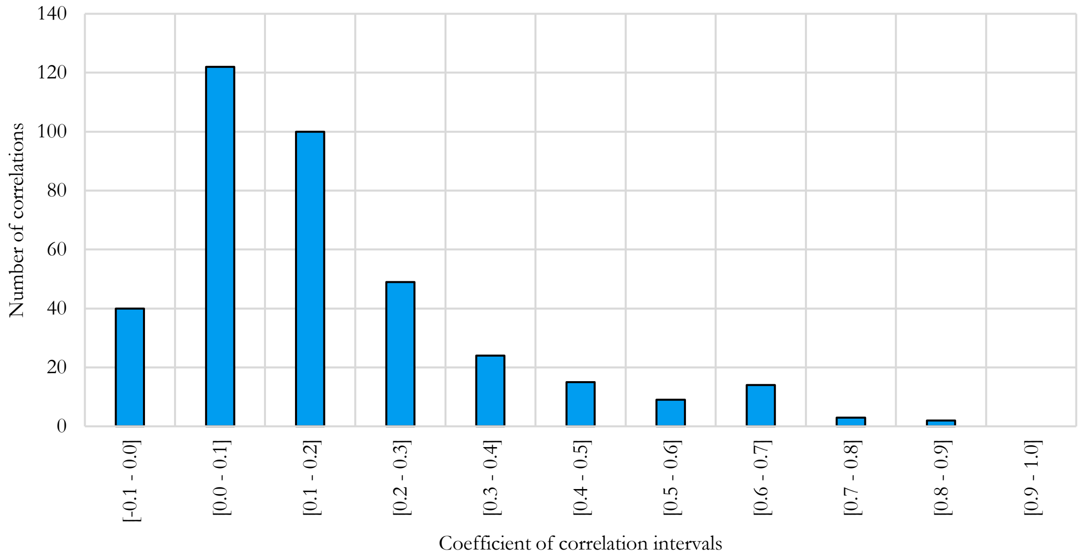

Figure 3-8. Distribution of coefficients of correlation between European countries with EEA relevance in 2021

Sources: Hourly generation data from ENTSO-E's transparency platform **(ENTSO-E, 2022d)**

Notes: For this chart, we calculated the coefficients of correlation between hourly wind generation time series in 2021 for all European countries with EEA relevance. The chart corresponds to a histogram of these correlation coefficients, where the y axis shows the number of correlation coefficients found in each interval on the x axis.

Figure 3-8 shows the number of country-pair wind correlations by correlation range level. As it can be observed, most country-pair wind profiles are uncorrelated, 70% of them lie within in the range from -0.1 to 0.2, which proofs a potential to exploit the complementarity from the uncorrelation of wind profiles across Europe.

The aggregation of European wind profiles reduces the overall generation variability and increases the overall minimum available generation from wind, which supports both a stable and more certain wind output and thus less flexibility needs and increased security of supply on basis of VRE production.

We find evidence of geographical complementarity of wind energy in Europe in two different aspects. First, the European aggregated wind profile presents a higher minimum wind generation (the point of departure of the distribution function from the x axis) than any individual country. Second, the European aggregated wind profile shows a more stable curve in the range from 20 to 40% of the installed capacity.

Figure 3-9 displays the distribution of wind generation for Germany and European aggregated data. The two effects mentioned earlier are observable (which would be the case for other countries as well). The minimum generation increases to around 6% of the installed capacity and the wind distribution is flattened. The sharing of wind resources between European countries can therefore generate a more stable wind generation profile than the wind profiles of individual countries. Countries can benefit from each other’s wind profiles if the necessary interconnection infrastructure is in place.

The right level of interconnection between countries must of course consider other factors analysed in a more complex cost benefit analysis, where the socioeconomic welfare benefits of investing in the interconnectors must outweigh the costs of the investment and operation. The analysis in this report simply points to the contribution of cross-border interconnectors to exploit the geographical complementarity of wind resources across Europe.

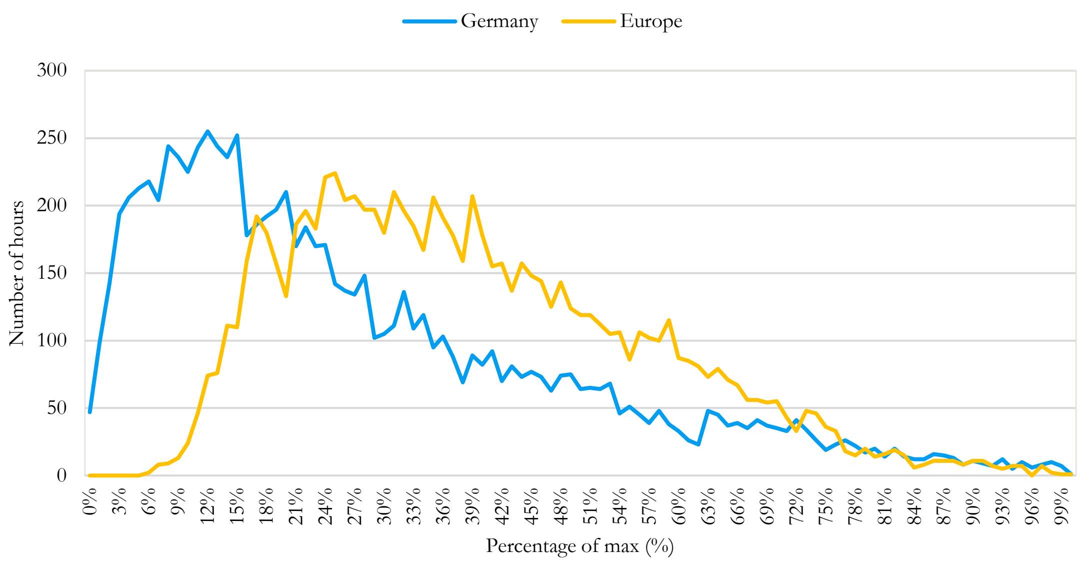

Figure 3-9. Wind generation distribution functions for Germany-and European aggregated data in 2021.

Sources: Hourly generation data from ENTSO-E's transparency platform **(ENTSO-E, 2022d)**. **Note**: European aggregated refers to European countries with EEA relevance subject to the availability of the data on the ENTSOE transparency platform.

The smoothening or flattening effect resulting from the aggregation of European wind generation can be measured with the standard deviation of hourly wind power profiles. Figure 3-10 shows that the standard deviation of aggregated European wind generation is around 24% lower than the average of individual country wind profiles. This result is consistent in all years analysed. The flattening effect achieved by sharing wind resources across European countries brings an overall more stable generation output and thus lower flexibility needs to cover the higher variability that would be obtained for isolated country systems. When it comes to hours with high wind production however, the difference between single countries and the whole EU is not as significant. In this regard it may even be harder to achieve hours with e.g., 100 % wind production throughout the continent, compared to smaller regions.

It is observed that the minimum hourly VRE generation can increase from around 0% of installed capacity for individual countries (Germany) to 6-10% for European aggregated VRE resources. In other words, taking all European countries together, there will be no hour within a year where VRE production is below 6 % of installed VRE capacities.

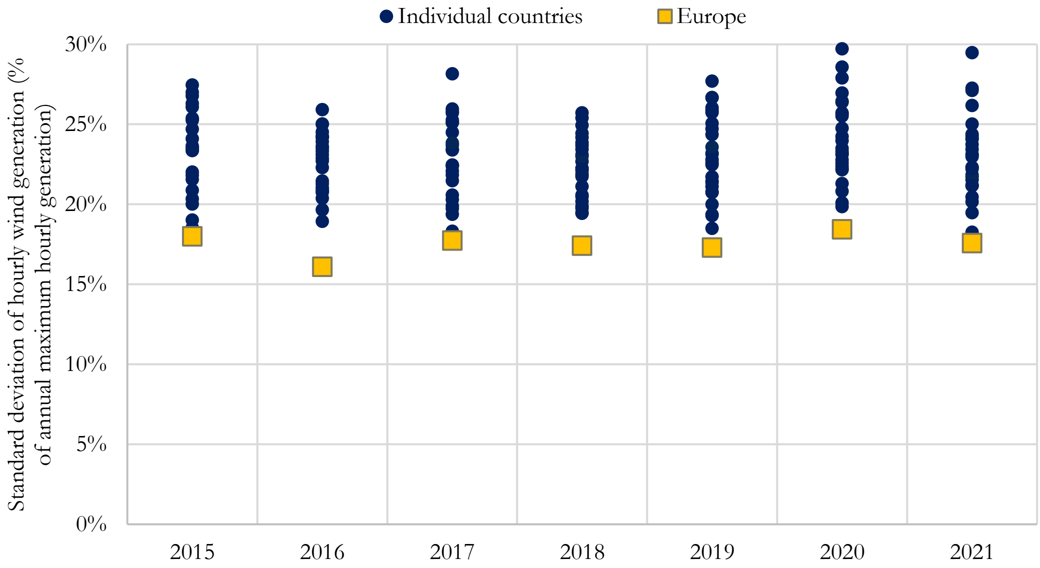

Figure 3-10. Standard deviation of wind power profiles by country and year.

Sources: Hourly generation data from ENTSO-E's transparency platform **(ENTSO-E, 2022d)**

Notes: Each point corresponds to one country and year and aggregated European values are presented as squares.

European countries can be clustered according to their wind correlation and help identify where to develop interconnection capacity to better exploit the complementarity of wind resources.

Last, we have evaluated whether average wind correlations may be higher within specific clusters. Wind correlations have been analysed for groups of countries, splitting Europe into different regions with correlated wind profiles. Nine clusters have been identified, as indicated in

The clusters have been arranged manually departing from groups of neighbouring countries geographically separated, e.g., Iberia from Continental Europe separated by the Pyrenees. The initial clusters were adjusted by adding countries when these resulted in a higher average coefficient of correlation or removing them when these resulted in a lower average coefficient of correlation between all country pairs within the cluster. Note that there are different clustering methods for data analytics such a “k-means”, based on iterative algorithms that successively recalculate the clusters based on a quantitative metrics such as the distance to the cluster centre. Thus, there may be other clustering arrangements with higher correlation levels than the ones displayed below. The aim of the clustering is to show the correlation differences between groups of countries within Europe, which can point to the importance of interconnectors to profit from wind resource diversity in Europe.

Table 3-2 below, for which the correlation between the countries is higher compared to the average coefficient of correlation between all European countries analysed in this work. While the average wind correlation in Europe is 0.18, in these clusters, wind correlations range from 0.55 in Scandinavia to 0.72 in Continental Europe Northwest. The map in Figure 3-11 illustrates these clusters with their average wind correlations.

The clusters have been arranged manually departing from groups of neighbouring countries geographically separated, e.g., Iberia from Continental Europe separated by the Pyrenees. The initial clusters were adjusted by adding countries when these resulted in a higher average coefficient of correlation or removing them when these resulted in a lower average coefficient of correlation between all country pairs within the cluster. Note that there are different clustering methods for data analytics such a “k-means”, based on iterative algorithms that successively recalculate the clusters based on a quantitative metrics such as the distance to the cluster centre. Thus, there may be other clustering arrangements with higher correlation levels than the ones displayed below. The aim of the clustering is to show the correlation differences between groups of countries within Europe, which can point to the importance of interconnectors to profit from wind resource diversity in Europe.

Table 3-2. Wind energy clusters in Europe based on coefficients of correlation.

Cluster	Cluster code	Countries	Correlation
Continental Europe Northwest	CENW	BE, FR, LU, NL	0.72
Continental Europe East	CEE	BG, RO	0.69
Iberia	IB	ES, PT	0.69
Continental Europe North	CEN	DE, PL	0.65
British Isles	BI	GB, IE	0.65
Baltic countries	BALT	EE, LT, LV	0.64
Continental Europe Centre	CEC	CZ, HU, AT	0.62
Italy & Balkans	BALK	IT, ME, BA, HR	0.57
Scandinavia	SCA	SE, NO, FI	0.55
Europe	All	All countries	0.18

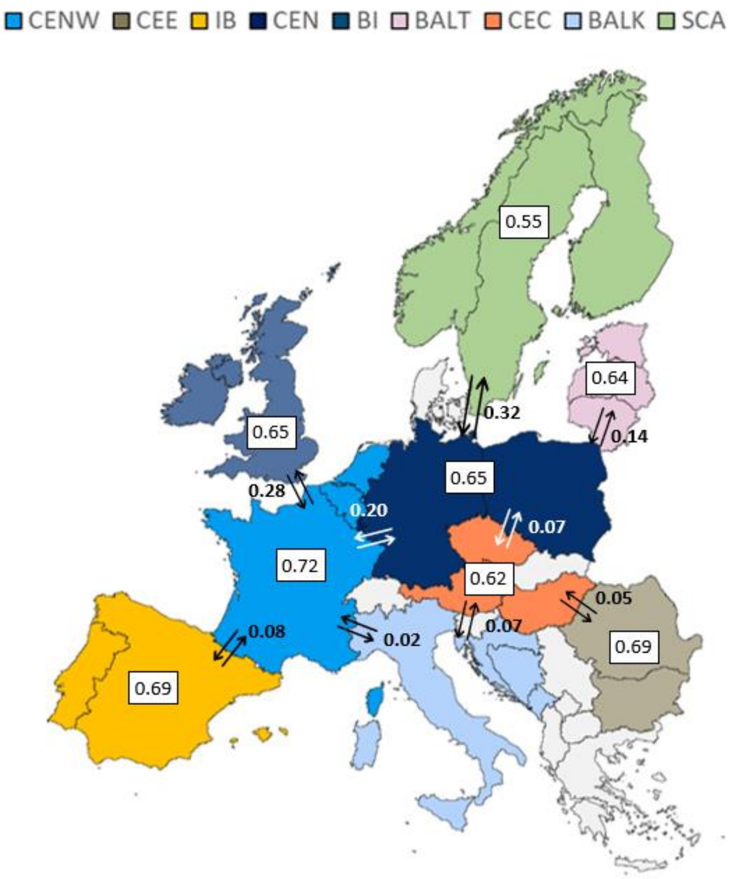

Figure 3-11. Wind energy clusters identified in Europe.

Sources: Hourly generation data from ENTSO-E's transparency platform **(ENTSO-E, 2022d)**

Notes: The coloured areas represent wind generation clusters. Each cluster correspond to a group of countries with an average wind correlation considerably higher (above 0.55) than the average wind correlation between all countries (0.18). The clusters have been selected from initial groups of countries by proximity and geographical separation from other clusters (e.g., Spain and Portugal form a cluster separated from Continental Europe Northwest). When the country increased the cluster wind correlation, the change was implemented. Grey coloured countries are those for which a cluster has not been identified or adding them to existing clusters reduced the cluster average correlation. The map is merely illustrative and multiple factors like offshore wind deployment can change the picture. Yet, it illustrates that it is the low correlation between clusters that has the potential to seize geographical complementarities. The analysis is based on historical wind generation profiles at Member State level (not wind profiles).

As it has been evidenced in the previous paragraphs, combining wind resources between European countries can bring a more stable wind generation with a higher overall minimum generation level. To allow the sharing of wind resources and exploit their geographical complementarity, sufficient cross-border interconnection capacity is needed. The identification of these clusters can help point more precisely where cross-border transmission infrastructure reinforcements could lead to a more efficient sharing of wind resources across Europe, instead of just demanding more cross-border interconnection capacities for all zones. The findings here must not be mixed up with other legislative targets however, such as the 70 % minimum available interconnection capacity target as described in chapter 2.

In the next step, we will add PV to the analysis. We spare complementarity analysis for solar alone, however. Solar generation profiles are highly correlated between European countries (0.8 on average) and differences in longitude/latitude and clouding between countries do not seem to make such a significant impact as to identify a complementarity effect of solar resources across Europe. Unlike wind, the European aggregated solar generation presents a similar distribution function to those of individual countries and its standard deviation lies in a middle range of individual countries' standard deviations. Unlike wind power, the aggregated European solar PV profile is not less variable than that of any individual country.

3.1.3 Geographical complementarity of wind and solar resources

The aggregation of European wind and solar profiles reduces the overall VRE generation variability and increases the overall minimum available VRE generation, which supports both a stable and more certain VRE output and thus less flexibility needs and increased security of supply

A recent study analysed wind and solar generation profiles in different countries and found that a higher share of wind, relative to solar power, fostered reliability to meet demand (Tong et al., 2021). (A. A. et al., 2020) concluded that electrical systems combining wind and solar obtain a higher renewable energy penetration rate, of up to 20% more than stand-alone wind or solar power systems. This same work also highlighted a reduction in needs for balancing or ramping capabilities thanks to wind and solar generation complementarity.

(Couto and Estanqueiro, 2020) evidenced the increased renewable integration in systems combining wind and solar generation, when compared with scenarios based on an individual renewable power source and stated that a combined development of wind and solar can reduce overall variability and peak residual demand (demand minus VRE generation). To maximise technology complementarity, it appears feasible to optimise VRE portfolios EU-wide. A study from the Belgian TSO Elia finds, for example, that a share of two thirds wind and one third solar generation would be optimal in northern Europe to avoid a structural, season-long mismatch between electricity supply and demand (Elia Group, 2021).

(Miglietta et al., 2017) found that the maximum wind potential in Europe is located in high latitudes in winter, but it shifts to specific areas in the Mediterranean Sea during summer. This study also evidenced some degree of local complementarity between wind and solar across many regions in Europe. (Christian M. Grams et al., 2017) also concluded that weather regimes provide a meteorological explanation for multi-day fluctuations in Europe's wind generation and can help guide new deployment pathways that minimize wind variability.

In this study it is found that the aggregation of VRE generation (wind, solar PV) across Europe has complementarity effects: the generation profiles are flattened, and the minimum generation level is increased. This can be observed in Figure 3-12 - left, where 2021 VRE generation duration curves (hourly VRE generation timeseries presented in ascending order) for individual countries and for European aggregated values are compared.

The European aggregated VRE generation duration curve is more stable (closer to a horizontal line, which would be a constant baseload production) compared to any individual country and the minimum production is around 10% of the overall VRE capacity, while this is close to zero for all individual countries. This is, at any given hour, we can at least count on 10% of VRE generation capacity in Europe, while for any individual country, we can find hours with close to zero generation. The sharing of VRE resources across Europe increases the certainty of VRE generation availability. On the right plot of Figure 3-12, the flattening effect from the European aggregation of VRE resources is also evidenced in a lower standard deviation for hourly VRE generation profiles compared to the average of individual country profiles observed in all years of the period analysed, 2015-2021 (an average 23% lower standard deviation).

If we take a closer look at the duration curve of VRE generation in Europe (left plot), the most adverse hour has an 8.5% VRE generation (minimum available VRE power). For the worst 20 hours (0.2% of the time), VRE generation is below 12%, and for 134 hours (1.5% of the time), VRE generation is below 15% of the installed capacity. Read oppositely, in 98.5% of the hours, VRE generation is above 15% of the installed capacity.

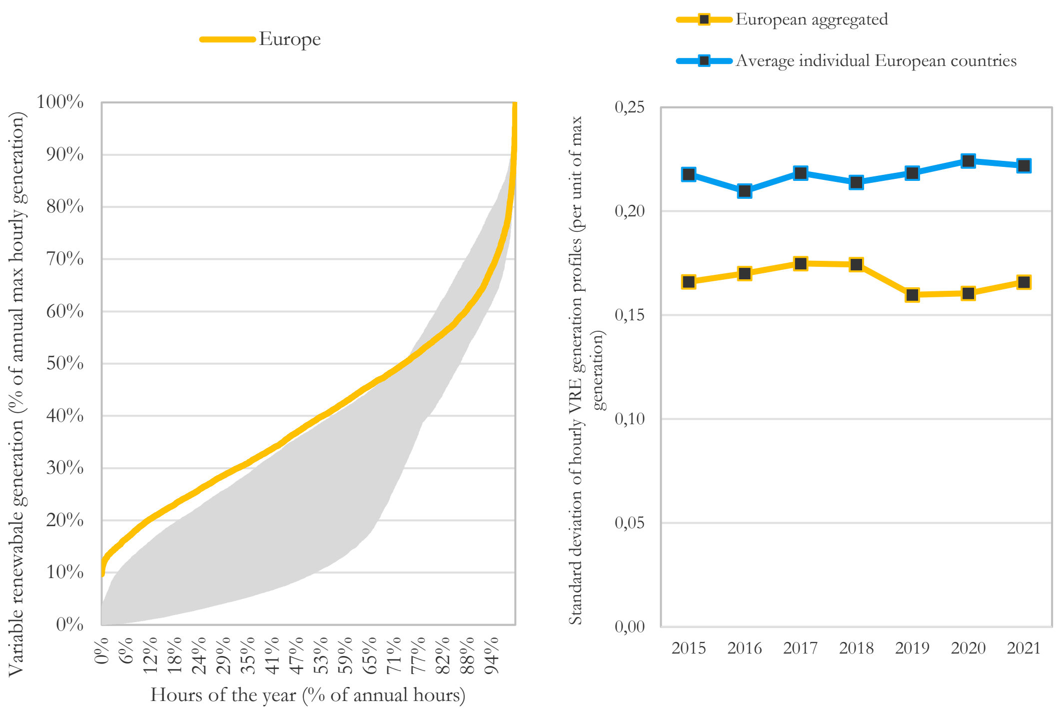

Figure 3-12. Left: Duration curves of VRE generation in Europe. Right: standard deviation of hourly VRE generation profiles in Europe.

Sources: Hourly generation data from ENTSO-E's transparency platform **(ENTSO-E, 2022d)**

Notes: Left chart: Duration curves of VRE generation for aggregated European generation (yellow curve) and for individual European countries analysed in this work (shaded area shows min-max range of all individual countries and grey curves for selected countries) in 2021. Right: standard deviation of hourly VRE generation profiles for European aggregated VRE generation (yellow curve) and average results for individual European countries (blue curve). The European countries analysed in this work are those with EEA relevance subject to availability of data.

The aggregation of European VRE resources can minimize the impact of localized Dunkelflaute events occurring in specific countries

With a focus on persistent wind and solar low generation events, an analysis can be made on the so-called Dunkelflaute events. In this report, a Dunkelflaute event has been defined as a period with wind and solar capacity factors below 20% for at least 24 successive hours, taken from (Bowen et al., 2021). This report finds that the aggregation of VRE generation across Europe decreases the number and duration of Dunkelflaute events. It has been proven that these events are mostly localised in specific regions. No such event has occurred simultaneously in all European countries analysed in this work in the period 2015-2021. For aggregated European VRE generation, no event has occurred either. The maximum number of successive hours with a capacity factor[24] below 20% for the aggregated VRE European generation has ranged from 15 to 20 hours in the period 2015-2021. The maximum duration of low wind and solar generation events is presented for Germany and European aggregated VRE generation in Figure 3-13 (left). Figure 3-13 (right) shows the maximum duration of Dunkelflaute events for all individual countries (with complete hourly wind and solar data) in 2021. European aggregated

[24] Capacity factor is the ratio of the electricity produced for the period considered to the electricity that could have been produced at continuous full power operation during the same period.

data has of course the lowest maximum duration, which can go up to 149 hours in Great Britain. A well interconnected European electricity system can therefore reduce the impact of national or regional Dunkelflaute events by relying on other countries wind and solar resources not impacted by those weather conditions leading to simultaneous and sustained wind and solar generation.

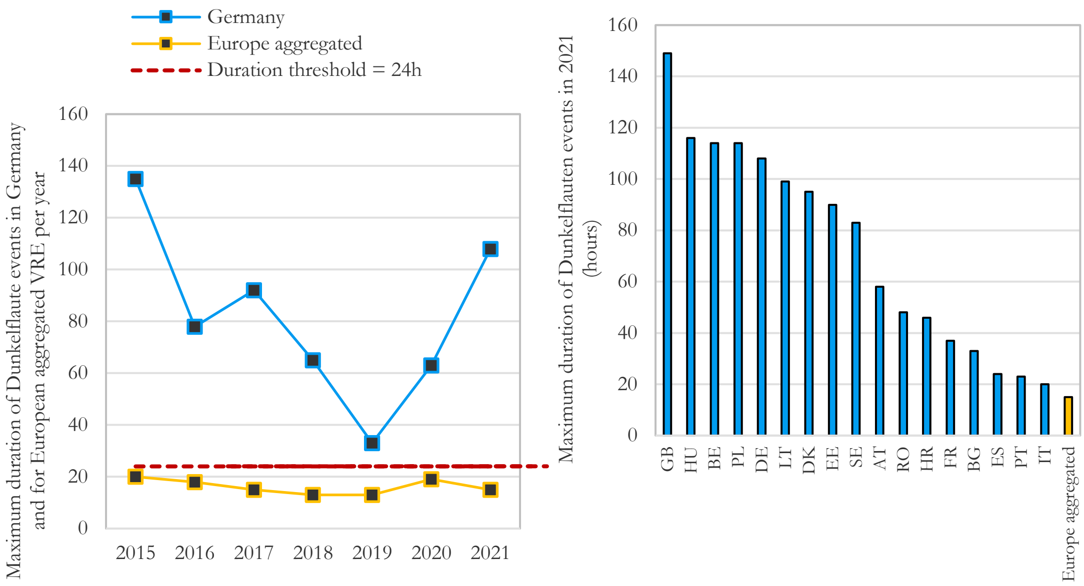

Figure 3-13. Maximum duration of Dunkelflaute events for selected individual European countries and for aggregated VRE generation.

Sources: Hourly generation data from ENTSO-E's transparency platform **(ENTSO-E, 2022d)**. **Notes:** the geographical scope covers European countries with EEA relevance subject to availability of data.

Notes: Left: maximum duration of Dunkelflaute events per year for German and European aggregated VRE generation (all European VRE generation summed as one time series). Right: maximum duration of Dunkelflaute events in 2021 for VRE generation in individual countries and European aggregated VRE generation.

Figure 3-14 shows the monthly distribution of Dunkelflaute events (average duration on the left plot and number of events on the right plot) in a selection of European countries, where the European average is also displayed. As it can be observed, most events manifest in the winter months and there are not any in the summer months. The higher likelihood of these events in the winter months also coincide with a higher electricity demand in the heating season. Winter months are more vulnerable to situations of VRE deficit, relative to demand, and thus may need additional flexibility resources as well as energy efficiency and savings measures, to compensate any lack of VRE generation relative to demand.

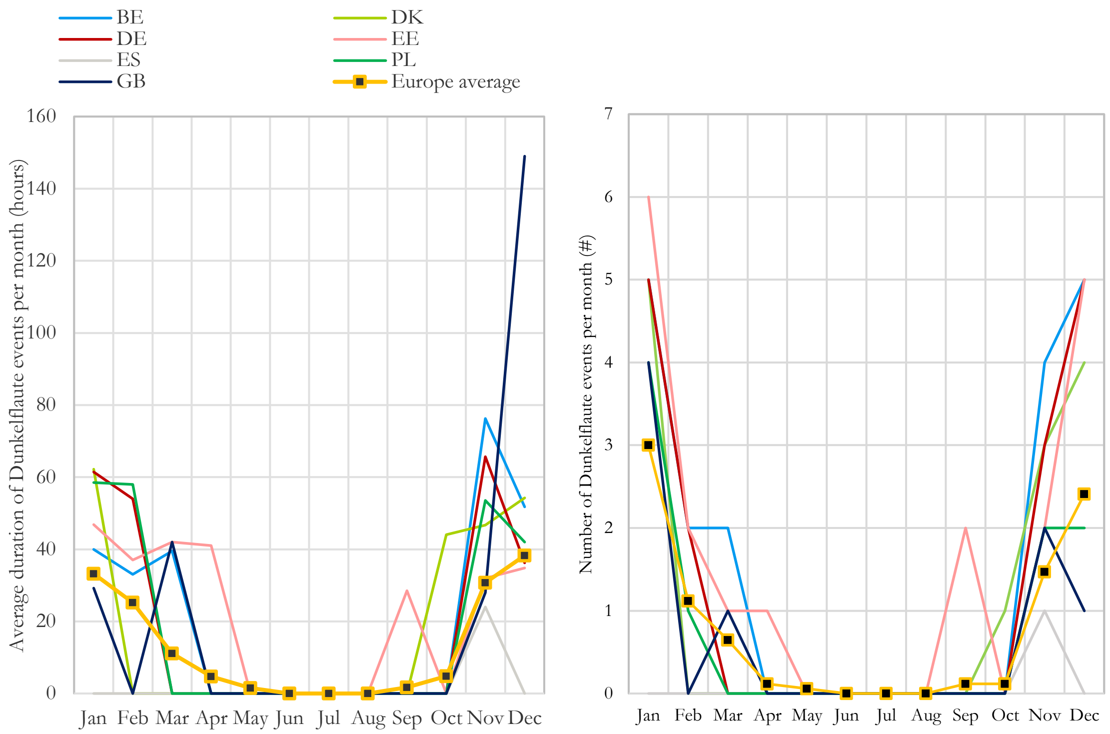

Figure 3-14. Average duration and number of Dunkelflaute events in selected European countries and average of European countries scoped in this work in 2021.

Sources: Hourly generation data from ENTSO-E's transparency platform **(ENTSO-E, 2022d)**

Notes: Left: average duration of Dunkelflaute events per month in selected countries and average in European countries. The average for Europe is calculated as the average of the average Dunkelflaute event duration per country for all countries scoped. Right: Number of Dunkelflaute events per month in selected countries and average in European countries. The geographical scope of this analysis covers European countries of EEA relevance subject to availability of data.

3.2 Residual demand and residual demand variation

The quantitative assessment of VRE excess and deficit in the European electricity system is based on historical data as well as for prospective levels of VRE by 2030. It evaluates the system ***residual demand*** *(difference between demand and VRE generation)*, which can take both positive values (demand > VRE generation) and negative values (demand < VRE generation).

The first analysis examines the quantitative requirement for energy resources that can compensate all VRE excess and deficit situations. These resources can include dispatchable generation, flexible demand, storage, or infrastructure, which can help meet the generation-demand balance in the system. These energy resources can cover a ***positive residual demand (VRE deficit)*** by increasing generation, reducing demand, importing lower-cost generation from another market zone, or discharging stored energy to the grid.

Conversely, when ***residual demand is negative (VRE excess)***, energy resources compensate the VRE generation-demand imbalance by increasing demand, exporting VRE generation to another market zone, charging storages from the grid or as a last option to decrease VRE generation (curtailment).

Our analysis does not cover market dynamics that naturally emerge in reaction to price signals. For instance, large consumers that participate in wholesale markets are only willing to purchase electricity below a certain price. This demand sensitivity to prices is expected to reach a wider range of consumers as dynamic tariffs gain momentum and so the demand curve will become more adaptive to the system needs in the future, depending on whether there is excess or deficit of VRE generation.

The case of VRE excess should not be a major concern for adequacy or operational security. As prices will get negative, the market is expected to react to it, for instance by producing renewable-based hydrogen. The case of VRE deficit (when residual demand is positive) is therefore of higher relevance to policymakers and electricity market stakeholders from an energy adequacy and security of supply perspective.

The second analysis focus on flexibility needs. The International Energy Agency defines power system flexibility as the ability to respond in a timely manner to variations in electricity supply and demand (International Energy Agency, 2019), but there are other definitions of flexibility needs. (Yang, Ce & Sun et al., 2022) mentions a definition from The North American Electric Reliability Council (NERC), where flexibility is defined as the ability to use system resources to meet load changes. (Yang, Ce & Sun et al., 2022) also includes a definition for flexibility as the ability to increase/decrease energy production (or alternatively decrease/increase demand) with a certain rate and ramp duration.

(EC, 2019h) defines flexibility as the ability of the power system to always cope with the variability of the residual load curve. Finally, (Art 2 (80) in the amended Electricity Regulation 2019/943, now a draft proposal) defines flexibility for the first time in a legal manner, where flexibility means the ability of an electricity system to adjust to the variability of generation and consumption patterns and grid availability, across relevant market timeframes.

This report uses the methodology from **(EC, 2019h)** to quantitatively examine the flexibility needs in the European electricity system. Following this methodology, flexibility needs are based on the variability of residual demand as assessed under three different time scopes: daily, weekly, and annual. These three different time scopes can reflect short, medium, and long-term flexibility needs in the system.

The resources to supply these different flexibility needs can also be different. For example, batteries can be an adequate flexibility resource to manage short-term flexibility needs, used for price arbitrage or balancing services. However, batteries will most likely not be used for long-term energy storage. For such long-term flexibility needs, other resources are needed, like the use of hydropower reservoirs or a future hydrogen system.

Other metrics can also be used to evaluate flexibility needs. (A. Herath et al., 2021) uses a metric based on net load forecast uncertainty. In **(ENTSO-E, 2021c)**, ENTSO-E mentions ramping flexibility needs, which measure daily residual load gradients, and scarcity period flexibility needs, which are focused on continuous periods of low VRE generation. **(EC, 2019h)** also includes alternative metrics like the difference between minimum and maximum residual demand, the average hourly ramping rate per hour of the day, and various analyses based on the residual demand duration curve.

In the future electricity system dominated by variable renewable generation, flexibility is the lever to always maintain the supply-demand balance. Flexibility is used to cover all VRE deficit and excess for all hours and to provide the ramping up and down capabilities to adapt to changes in the system load from one period to the next.

Flexibility needs is thus of paramount importance in energy planning exercises. Since flexibility may be provided by many types of resources (supply side, storage, infrastructure, and demand side), holistic perspectives of integrated energy systems are needed to capture the flexibility potential from other sectors to the electricity system, such as with EVs (transport), heat pumps (heating/cooling systems), or PtX plants (hydrogen systems). Not considering all potential flexible resources available can risk biasing energy plans towards specific solutions (e.g., focus on firm dispatchable generation, while demand response can provide a similar flexible role in the system). Acknowledging the importance of flexibility in the electricity system, the European Commission's proposal of March 2023 intend to improve the Union's electricity market design (EC, 2023b) and provide new rules regarding the assessment of the flexibility needs by Member States, the possibility to introduce flexibility support schemes and design principles for such flexibility support schemes.

In the following numbers for reduced or increased energy demand or production are compared against a baseload power plant. The power plant used is an 800 MW block running in 90 % of the hours of the year (8,760 hours). The numbers are only indicative high-level numbers.

Key insights from the residual demand analysis

Residual demand - VRE deficit and excess

1. From 2021 to 2030 the annual VRE deficit is reduced by 42% with a VRE generation growth of 250%. In absolute terms, the VRE deficit reduction is around 1,047 TWh. Equivalent to the annual generation of 166 baseload thermal power plants.
2. By 2030, existing and planned interconnectors can reduce annual VRE deficit by 133 TWh (and excess by the same amount) compared to not having any interconnectors. This is equivalent to the annual generation of 21 baseload thermal power plants.
3. In 2030, an annual demand reduction of 7% (231 TWh) reduces the annual VRE deficit by 231 TWh, which means a 16% reduction of the VRE deficit in the scenario with the reference demand (equivalent to 37 baseload thermal power plants).
4. Despite rapid VRE generation growth, peak VRE deficits are barely reduced by 2030 without demand savings (from 449 GW in 2021 to 432 GW in 2030). Occurring only for a limited number of hours in any year, peak VRE deficits are due to infrequent situations of very low VRE generation relative to demand. The value of interconnectors is also limited in these peak events of VRE shortage (only 1% decrease compared to no interconnection). Demand response (peak shaving, demand shifting) or other time-flexibility resources like storages are more effective to face these peak events (13% decrease).
5. From 2021 to 2030 annual VRE excess is overall increased from 0.2 TWh to 118 TWh (equivalent to the annual generation of 19 baseload thermal power plants).

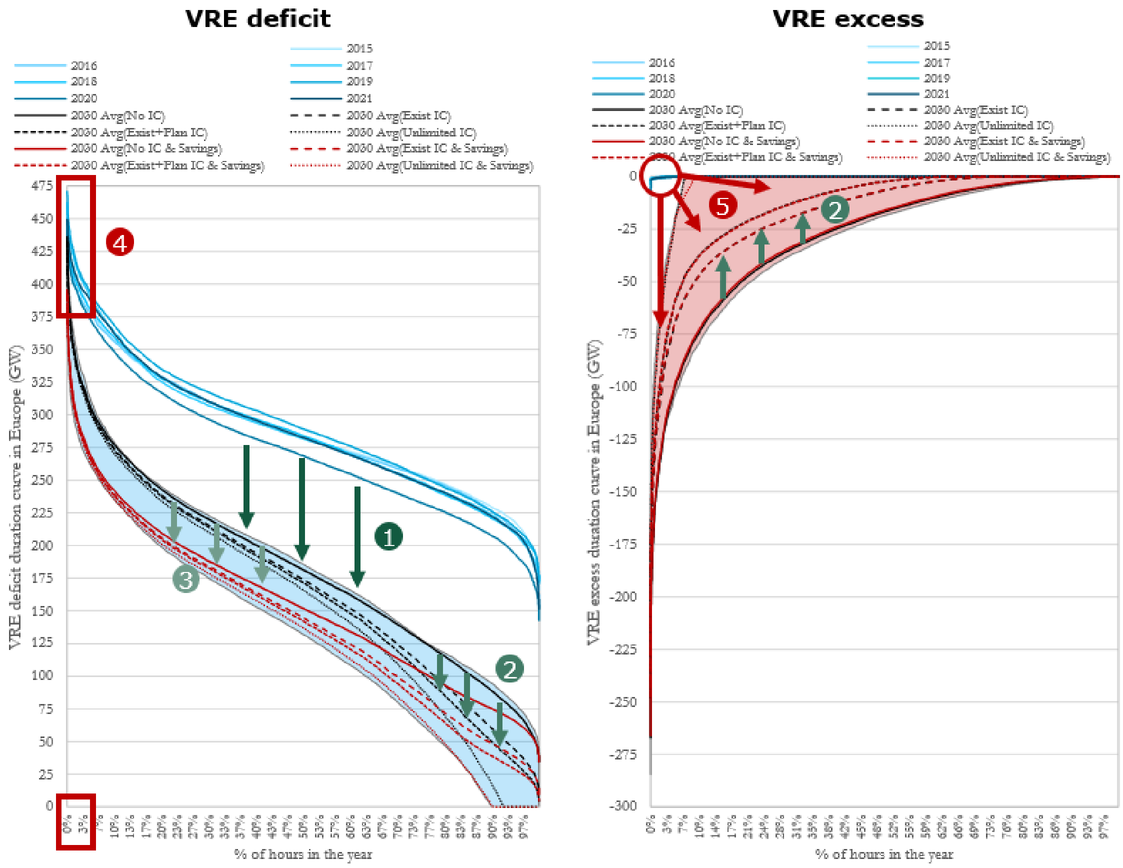

Figure 3-15. Duration curves for VRE deficit (left) and excess (right) from 2015 to 2030 under the different scenarios simulated, with the numbered key insights pointed in the figures.

Residual demand variation – flexibility needs

1. From 2021 to 2030 the VRE growth is estimated to result in overall increases in flexibility needs:
   a. 2.4-fold growth in daily flexibility needs or short-term flexibility (flexible resources that can adapt to hourly changes in residual demand every day). 362 TWh annual needs (existing + planned IC, no demand savings) represent an average hourly need of 41 GWh/h of flexible resources to adapt to hourly variations of residual demand.
   b. 1.8-fold in weekly flexibility needs or mid-term flexibility (flexible resources that can adapt to daily changes in residual demand every week). 242 TWh annual needs represent an average daily need of 661 GWh/day of flexible resources to adapt to daily variations of residual demand.
   c. 1.3-fold in annual flexibility needs or long-term flexibility (flexible resources that can adapt to monthly changes in residual demand every year). 168 TWh annual needs represent an average monthly need of 14 TWh/month of flexible resources to adapt to monthly variations of residual demand.
2. Existing and planned interconnectors result in an overall decrease of daily, weekly, and annual flexibility needs of 3 TWh (-1%), 30 TWh (-12%), and 15 TWh (-9%) respectively, compared to the scenario without interconnection.[25]
3. Demand savings and shifting (10% savings in non-peak hours, 5% in peak hours with the possibility of shifting) bring an overall reduction in daily, weekly, and annual flexibility needs of 24 TWh (-7%), 21 TWh (-9%) and 19 TWh (-12%) respectively compared to the scenarios without demand savings and shifting.

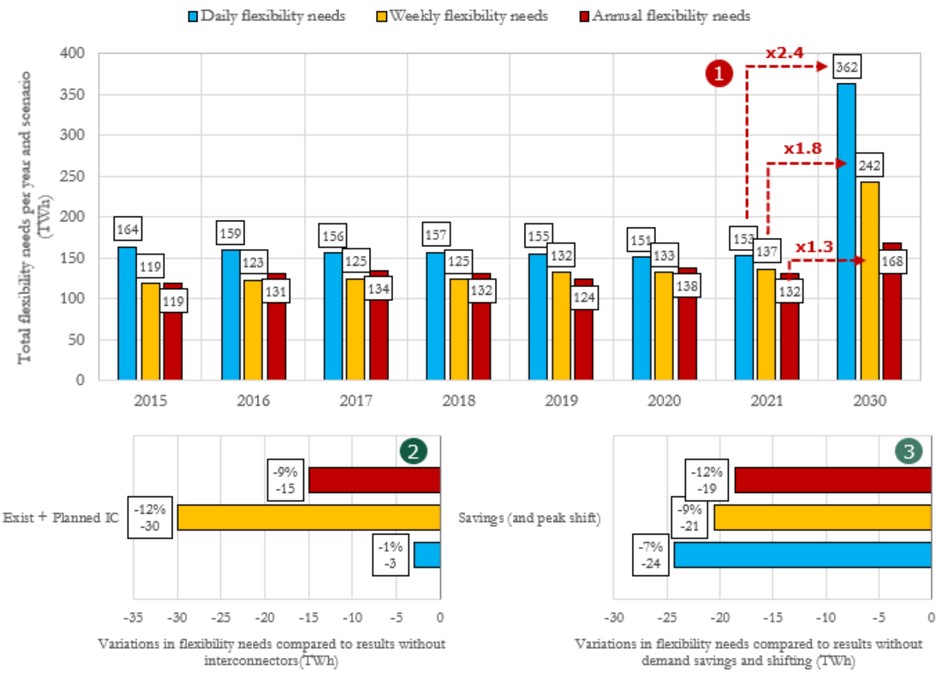

Figure 3-16. Key results from the flexibility needs (residual demand variation) analysis.

[25] The lower decrease in hourly flexibility needs compared to weekly and annual can be explained by the aggregation of residual demand over daily and monthly periods in the two latter. On an hourly resolution, interconnectors can result in some countries in a greater variability of residual demand and thus higher short-term flexibility needs. This does not happen when we aggregate the residual demand in longer time periods to estimate the weekly and annual flexibility needs.

Input data

The analysis is based on residual demand with an hourly resolution. Therefore, the input data needed are hourly VRE generation and demand for all zones of the European electricity system. As in the complementarity analysis, the geographical scope comprises European countries with EEA relevance. For historical data on VRE and demand, values are taken from the ENTSO-E transparency platform (ENTSO-E, 2022d). For VRE and demand projections, values are taken from the *Policy scenarios for delivering the European Green Deal* by the European Commission. These scenarios are REG, MIX and MIXCP[26]. Since the scenario results only include annual projections, hourly VRE and demand have been estimated using 2017 and 2021 historical hourly profiles factored to the annual projections of 2030[27].

Interconnection capacity is used in the analysis for 2030 projections. Existing interconnection capacity is based on the ENTSOE transparency platform (ENTSO-E, 2022d). For planned interconnectors, data is based on the projects of common interest (PCI) list under the TEN-E Regulation (European Commission, 2021).

Residual demand

Residual demand is defined as demand minus VRE generation. This is calculated for all bidding zones. To aggregate results for Europe, for each hour, positive and negative zonal residual demands are summed separately. As a result, two values for Europe for each hour is calculated, i.e., positive residual demand or VRE deficit and negative residual demand or VRE excess.

From these results are the peak values highlighted representing the extreme cases of VRE deficit and excess and total annual volumes.

Modelling of 2030 residual demand projections

Residual demand results for 2030 rely on the dispatch results from a simplified version of the European market coupling dispatch model, where demand is an exogenous parameter. On the generation side, there are two generation resources: VRE available generation per zone (bidding price = 0) and non-VRE generation per zone (equal bid price in all zones and hours). The latter is used to capture any VRE deficit relative to demand.

The model allows exchange of VRE electricity between zones limited by interconnection capacities. The purpose is to evaluate VRE integration in the system under different interconnection levels. Since the results are aggregated on a European scale, the analysis focus on how much VRE excess and deficit can be decreased in Europe through the connection of the different market zones.

We evaluate four different interconnection levels:

[26] **REG**: scenario relying on very strong intensification of energy and transport policies in absence of carbon pricing in road transport and buildings; **MIX**: scenario relying on both carbon price signal extension to road transport and buildings and strong intensification of energy and transport policies; **MIX-CP**: scenario representing a more carbon price driven policy mix that illustrates a revision of the EED and RED but limited to a lower intensification of current policies in addition to the carbon price signal applied to new sectors (EC, 2021e).

[27] Hourly VRE generation in 2030 = hourly VRE generation in 2017 or 2021 / VRE maximum generation 2017 or 2021 x VRE installed capacity in 2030 from scenario MIX, MIXCP or REG.

Hourly demand in 2030 = hourly demand in 2017 or 2021 x annual demand in 2030 from scenario MIX, MIXCP or REG / annual demand in 2017 or 2021

1. No interconnection
2. Existing interconnection levels
3. Existing and planned interconnectors
4. Infinite interconnection capacity.

The analysis also evaluates the impact on residual demand from demand savings and a certain degree of demand shifting. Demand savings and shifting have been implemented inspired by the recent European Commission emergency intervention to address high energy prices **(EC, 2022k)**. A reduction of 10% to the reference demand[28] in non-peak hours without VRE excess and 5% in peak hours (defined as the 4 weekday hours with the highest residual demand) is implemented in the model.

In addition, the 5% reduction in peak hours can be shifted to hours of VRE excess in case those happen before the following 4-hour peak period. This however does not occur for all weekdays, so demand shifting is limited to the occurrence of VRE excess between peak hour periods. The demand shifting allows the model to shift demand from hours with peak demand to hours with an excess of VRE production.

The expectations for flexible demand in the future are high regarding how active demand can react to system needs. Albeit that the demand response measures are implemented as exogenous parameters, they do inform on the possibilities of both reducing demand in general (- 10 %) and demand response (5 % demand shifting from peak to VRE excess periods).

Furthermore, new demand may adapt to VRE generation profiles better than existing electricity demand thanks to more flexible demand types (PtX, electric heating and cooling, smart EV charging). Note however that only classic electricity demand is considered in this analysis.

The total number of simulations amounts to 64 corresponding to the combination of the different input parameter variations: 4 interconnection levels, 2 demand scenarios, 4 VRE generation projections, 2 hourly generation and demand profiles (4 x 2 x 4 x 2 = 64).

Table 3-3 presents the different input parameters making up the 64 simulations.

Table 3-3. Scenarios simulated for 2030 projections.

Scenario input parameter	Variations on input parameters	Number of scenarios
Annual VRE generation and reference demand projection	NECP, REG, MIX, MIX-CP	4
Hourly profiles for VRE and demand	2017, 2021	2
Interconnection levels	No IC, Existing IC, Existing and planned IC, Unlimited IC	4
Demand variations	Reference demand, demand with savings and shifting	2
Total combinations		**64**

[28] The reference demand is the demand projection using 2017 and 2021 hourly profiles factored by annual demand projections from the scenarios MIX, MIXCP and REG.

3.2.1 Residual demand - Wind and solar generation excess and deficit

Increasing VRE generation decreases overall VRE deficit situations, but special attention must be put on hours of high VRE deficit, when adequate resources (dispatchable generation, storage, and demand response) must be in place.

The increasing shares of VRE planned for 2030 reduce VRE deficit situations and therefore the needs for other non-VRE generation resources. On a European annual basis, for the scenario with existing and planned interconnectors, the reduction of non-VRE generation is significant, from an average of 2,500 TWh in the period 2015-2021 to an average of 1,350 TWh in 2030, a decrease of 46% or 1,150 TWh. As a comparative order of magnitude, 1,150 TWh represent the annual generation from 182 baseload power plants.

A VRE deficit duration curve is shown on Figure 3-17 (bottom left) considering the various interconnector scenarios previously listed. The results are shown for each interconnector scenarios as the average when varying the other parameters (demand, VRE generation projections, hourly generation, and demand profiles, see Input data). The VRE excess and deficit are shown with their respective minimum and maximum variations.

Peak VRE deficits refer to situations of extremely low VRE generation relative to demand, during which the electricity system needs to be able to respond appropriately. Peak VRE deficits are very infrequent conditions, occurring only for a very short number of hours in a year. Moreover, with VRE deficit levels correlated with electricity demand levels, the peak VRE deficits match with the morning and evening peaks in electricity demand.

The less intense the VRE deficits become, the more they increase in frequency; but, as a rule, very high (peak) VRE deficits occur at a very low frequency. As such, by 2030 a maximum hourly VRE deficit (calculated at circa 440 MWh/h) would occur in 0.0% of all hours in a year (i.e., in only 1 hour) and a 20% smaller VRE deficit (of 353 MWh/h) would occur in 2% of all hours in a year (156 hours).

Therefore, in 90% of the hours, the VRE deficit in 2030 is below 260 GW on average for all scenarios simulated. This is a 37% lower VRE deficit than the peak. Successively, in 70% of the hours the VRE deficit is below 200 GW, which is a 52% lower VRE deficit than the VRE deficit peak.

The VRE excess curve (bottom right) shows a steeper curve (on the 0 to 30% of hours range) than for VRE deficit. This means that extreme events are even more rare. For example, in 70% of the hours VRE excess is below 20 GW.

Irrespective of scenario, the results show the same trend – a high increase in VRE production reduces the need for energy production from other sources (TWh) but requirements on peak capacity (GW) from other sources are almost equivalent to today. The contribution from interconnectors is described in the following section.

Also of importance is the asymmetry in VRE excess and VRE deficit levels, which can limit the ability of storages to balance VRE deficit and excess of energy since these cannot bring additional electricity to the system, but rather exchanging electricity from times of VRE excess to times of VRE deficit. Therefore, according to this analysis, for VRE deficit and excess balance purposes, the storages contributions could be limited to 118 TWh annually (or the annual electricity generation from 19 baseload power plants). However, storages can also bring value to the system by charging electricity from the grid in times of low electricity prices and discharging it to the grid in times of high prices. This increases welfare or the more efficient market allocation even if the electricity charged is not from VRE excess generation.

Thus, VRE excess is comparatively a minor issue in terms of annual electricity to VRE deficit: 118 TWh VRE excess in 2030 compared to 1,350 TWh VRE deficit on average across scenarios. VRE excess events can achieve levels of 242 GW excess electricity in the system by 2030. This is still lower than the peak VRE deficit of 455 GW.

Figure 3-17. VRE excess (red) and deficit (blue) per year and scenario in 2030 in Europe.

Sources: Hourly generation and demand data from ENTSO-E transparency platform (ENTSO-E, 2022d) ; 2030 annual projections from the Policy scenarios for delivering the European Green Deal **(EC, 2021e)** combined with historic hourly profiles from (ENTSO-E, 2022d).

Notes: Top left: peak VRE excess (red) and deficit (blue) per year and scenario in 2030. Top right: annual VRE excess (red) and deficit (blue) per year and scenario in 2030. Bottom left: VRE deficit duration curve per year and scenario. Bottom right: VRE excess duration curve per year and scenario.

Existing and planned interconnectors can reduce VRE deficit and excess by allowing the exchange of VRE generation from zones with VRE excess to zones with VRE deficit. However, their value is limited in peak VRE deficit periods of generalised VRE shortage.

Cross-border interconnectors can be one of the key energy infrastructure resources to help integrate the growth of VRE generation in the future. The value of interconnectors in reducing VRE deficit and excess has been estimated in this analysis by comparing simulation results for four interconnection levels.

Figure 3-18 displays the differences between each scenario with interconnectors and the results without interconnection. Hence these values can be taken as the value of the different interconnection levels in reducing VRE excess and deficit. The results are again shown for each interconnector scenario as the average when varying the other parameters (demand, VRE generation projections, hourly generation, and demand profiles, see Input data).

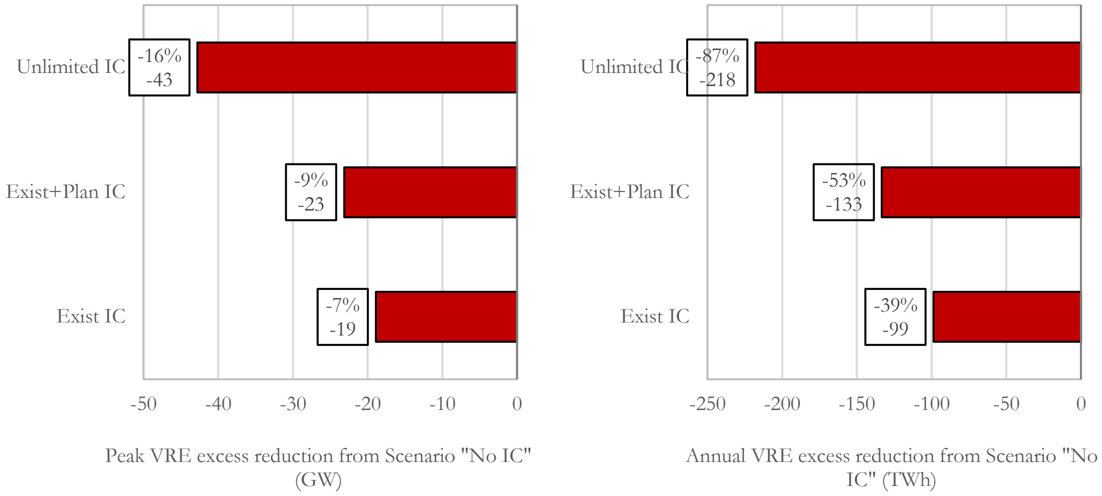

Figure 3-18. Value of interconnectors in reducing overall VRE excess in Europe.

Sources: Hourly generation and demand data from ENTSO-E's transparency platform **(ENTSO-E, 2022d)** ; 2030 annual projections from the Policy scenarios for delivering the European Green Deal **(EC, 2021e).** combined with historic hourly profiles from **(ENTSO-E, 2022d)**.

Notes: Reduction in peak (left plot) and annual (right plot) VRE excess from successive interconnection levels compared to a scenario without interconnectors. The values displayed are averages from all simulations performed per interconnection scenario.

The analysis indicates that existing and planned interconnectors can reduce the exceptional situations of peak VRE excess by 23 GW (9% reduction) and peak VRE deficit by 4 GW (1% reduction) compared to the scenario without interconnectors. Peak VRE deficits are, as a rule, very infrequent conditions (a few hours per year) of very low VRE generation relative to demand.

They occur more often during morning and evening demand peak hours. In such peak situations, interconnectors show a limited value because of the similar demand hourly profiles across European countries that make VRE generation lower than demand in all European countries. Since interconnectors can only bring value by exchanging electricity between market zones, in peak VRE deficit events, increased non-VRE generation, electricity released from storages or demand reduction is needed.

The 1% reduction of peak VRE deficit with interconnectors compared to the scenario without interconnectors only means that in the worst-case hour of VRE deficit relative to demand, interconnectors cannot reduce more than the 1% overall deficit since VRE deficit is present in most countries. This, however, should not be taken as the value of interconnectors in the system in this hour, as there are other decarbonised flexible resources in the system, like hydropower, biomass-fired units, nuclear power plants, storages or demand-response, which are not considered in this quantitative analysis, but which can support the system in these adverse hours, and whose value can be spread across countries thanks to cross-border interconnectors. The worst hour per country in terms of VRE deficit relative to demand does not simultaneously happen in all countries. Interconnectors come again as a valuable infrastructure for the system to back-up countries when VRE shortages occur supported by VRE excess or flexible resources from other countries.

In annual terms, VRE excess and deficit can be reduced by 133 TWh for the scenario with existing and planned interconnectors (reduction of 53% of VRE excess and 10% of VRE deficit). Annual VRE excess and deficit reductions are similar since interconnectors flow VRE generation from VRE excess zones to VRE deficit zones. Thus, having the existing and planned interconnectors in place by 2030 together with the renewable development plans will save the equivalent annual electricity generation from 21 baseload power plants (133 TWh), by sharing VRE production across interconnectors between countries and market zones.

The value of interconnectors in this analysis is limited to the increase in efficiency of VRE integration between countries in Europe. We analyse how much VRE generation excess in some zones can be transported to zones with VRE generation deficit (and thus reductions in VRE deficit and excess), which also corresponds to avoided VRE generation curtailment if the interconnectors were not there. Yet, the value of interconnectors goes beyond this effect. For example, ACER estimated (ACER, 2022a) that cross-border trade delivered 34 billion EUR of additional socioeconomic welfare in 2021, originating from a more efficient electricity market dispatch, compared to a situation without interconnectors where generation and demand agents are restricted to their national markets.

Generalised demand savings applied over VRE deficit hours impact the annual VRE deficit proportionally, but demand response measures, like peak shaving or demand shifting, can boost the adequacy benefits of demand for the grid.

Demand savings implemented have for this analysis been implemented as 10% of demand savings in non-peak hours without VRE excess and 5% in peak hours shiftable to hours of VRE excess before the following peak hour period inspired by the recent European Commission emergency intervention. In total it represents an annual demand reduction of 7% compared to the reference demand projections without any measures.

These measures have been introduced as an example of how demand savings and response can impact VRE deficit and excess. Albeit that such demand measures may not be fully realistic, as demand may be reacting more clearly to market price signals, the results give an indication of the potential impact of such measures.

Electricity demand is expected to increase by 2030 to help decarbonise other sectors such as buildings, transport, and industry. Demand projections for 2030 are taken from the Policy scenarios for delivering the European Green Deal by the European Commission.

The impact of the demand measures can be visualized on Figure 3-19, both for peak situations (left figure) and for annual energy (right figure). What can be observed from the results is that the 7% overall demand reduction (232 TWh on average for all scenarios) reduces the peak VRE deficit by 41 GW (-9% of VRE deficit with the reference demand) and 232 TWh of annual VRE deficit (-16%[29] reduction from the scenario with the reference demand). The demand saving measures applied have a direct proportional impact on VRE deficit situations (232 TWh demand savings, 232 TWh lower annual VRE deficit).

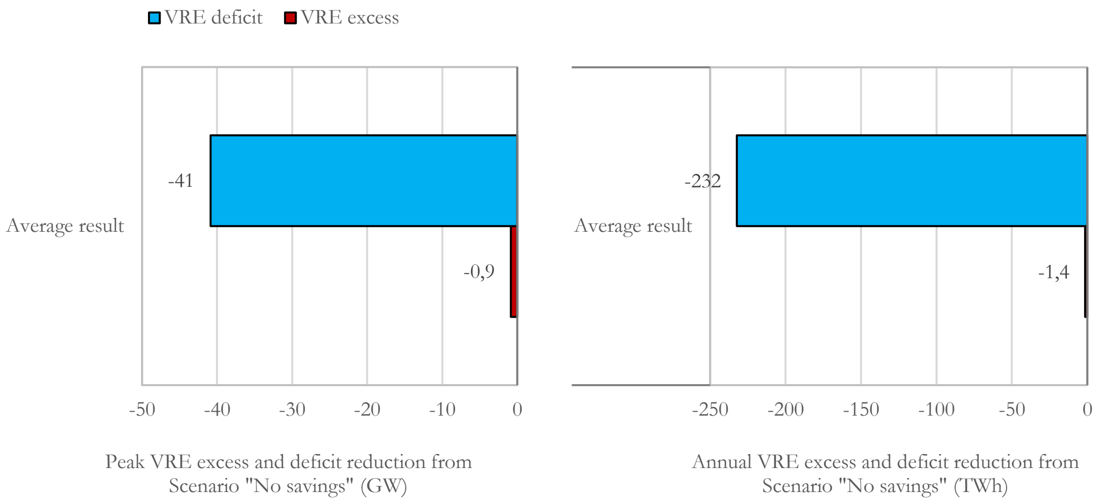

Figure 3-19. Value of demand-side measures applied in reducing overall VRE excess and deficit in Europe.

Sources: Hourly generation and demand data from ENTSO-E's transparency platform **(ENTSO-E, 2022d)** ; 2030 annual projections from the Policy scenarios for delivering the European Green Deal **(EC, 2021e).** combined with historic hourly profiles from **(ENTSO-E, 2022d)**.

Notes: Reduction in peak (left plot) and annual (right plot) VRE excess (red) and deficit (blue) from demand savings (and limited peak-hours shifting). The values displayed are averages from all simulations performed per demand scenario.

As mentioned earlier, demand can have larger impacts on both VRE excess and deficit by dynamically adapting its profile to VRE excess and deficit via market price signals. Demand response is thus expected to have a major role in the future electricity system. (DNV, 2022)

[29] It can be highlighted that it is possible to achieve a higher share of reduction over residual demand than the share of reduction in demand. For example, for a demand of 10 MWh and VRE generation of 5 MWh, residual demand would be 5 MWh (VRE deficit). If we reduce demand by 10% to 9 MWh, the new residual demand is 4 MWh (VRE deficit). While the decrease in demand is 10%, the resulting drop in residual demand is 20%. However, in absolute terms, the reduction in demand and residual demand is the same, 1 MWh.

estimates 121 GW and 100 GW of upward and downward[30] flexible demand capacity in the system by 2030, coming from industrial demand, battery energy storage systems (BESS), electric vehicles, and industrial and residential electric heating. The active participation of these resources was estimated to be 304 TWh and 303 TWh for upward and downward flexibility in 2030. Note that these numbers refer to explicit demand response in the wholesale market and are not restricted to hours of VRE excess and deficit, subject of this analysis. Therefore, results cannot be directly comparable, but they can be taken as a reference order of magnitude of demand response capacity and annual energy activation by 2030.

3.2.2 Residual demand variability - Flexibility needs

Residual demand variability is the metric used to quantify flexibility needs. The variability is calculated as the difference between residual demand and its average over time. Following the methodology from (EC, 2019h), flexibility needs are calculated as indicated below.

$$Total\ daily\ flexibility\ needs = \frac{1}{2} \cdot \sum_{day\ 1\ to\ 365} \left(\sum_{hour\ 1\ to\ 24} \left| residual\ demand_{hour} - average\ residual\ demand_{day} \right| \right)$$

$$Total\ weekly\ flexibility\ needs = \frac{1}{2} \cdot \sum_{week\ 1\ to\ 52} \left(\sum_{day\ 1\ to\ 7} \left| residual\ demand_{day} - average\ residual\ demand_{week} \right| \right)$$

$$Annual\ flexibility\ needs_{year} = \frac{1}{2} \cdot \sum_{month\ 1\ to\ 12} \left| residual\ demand_{month} - average\ residual\ demand_{year} \right|$$

Absolute values are taken from the sum of the differences and then divided by two since the sum of differences to the average equals zero. What is of interest in the metric is how variable the residual demand is from its own average.

A zero flexibility needs using this metric does not mean that there is no residual demand, but that the residual demand is constant. The underlying logic is that a constant residual demand does not need flexibility resources, but it can simply be covered by a baseload generation power plant (or a baseload constant demand reduction of the same amount).

The idea of calculating the flexibility needs at different time scales is that these can be supplied by resources able to balance residual demand fluctuations (positive and negative differences) and that the average residual demand, a constant flat positive or negative value, could be served by a baseload energy resource and thus not require any flexibility resources to actively adapt to fluctuations in the electricity system needs.

Figure 3-20 serves as an illustration of daily flexibility needs. The coloured areas represent the sum on the first equation above. As indicated earlier, flexibility needs are measured as the sum of the differences between residual demand and its average. The average flexibility needs are then set at the zero level on the y axis, and the coloured areas represent the differences between residual demand and its average. The sum of the blue and yellow areas is thus equal.

[30] Upward flexibility refers to the ability to decrease demand (or increase generation), while downward flexibility refers to the ability to increase demand (decrease generation).

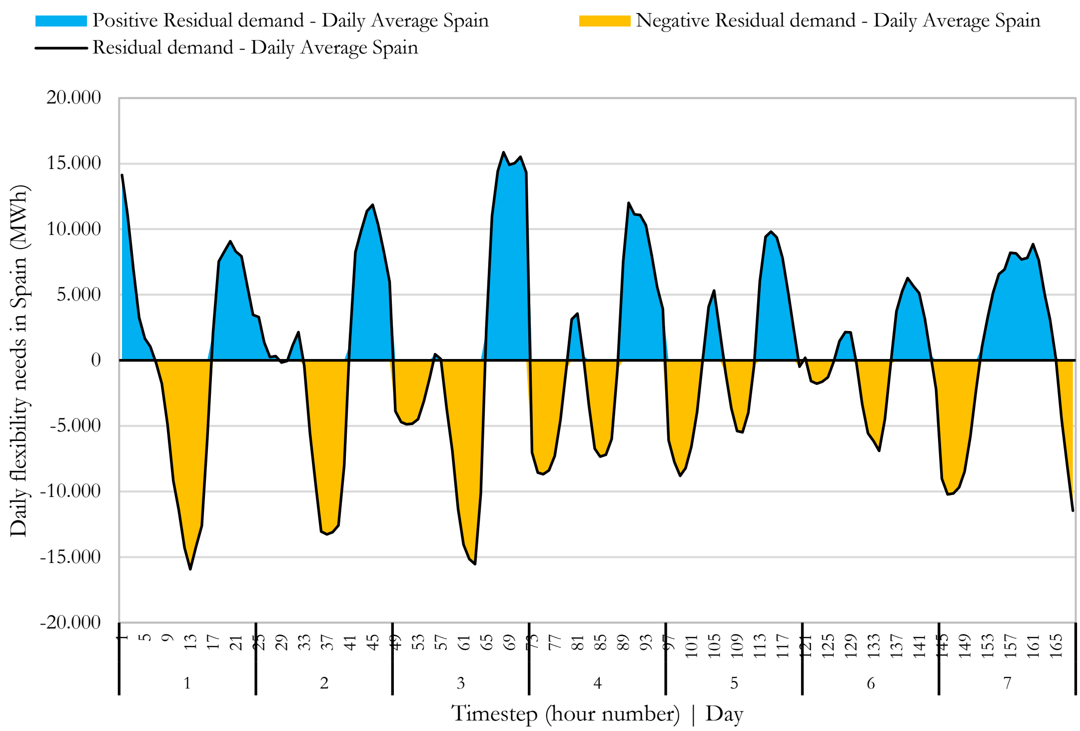

Figure 3-20. Illustration of daily flexibility needs.

Sources: Hourly generation and demand data from ENTSO-E's transparency platform **(ENTSO-E, 2022d)** ; 2030 annual projections from the Policy scenarios for delivering the European Green Deal **(EC, 2021e),** combined with historic hourly profiles from **(ENTSO-E, 2022d)**.

Notes: Illustration of daily flexibility needs in Spain on the first week of 2030. Total flexibility needs correspond to any of the coloured areas (blue: sum of positive differences between residual demand and the weekly average residual demand, yellow: sum of negative differences between residual demand and the weekly average residual demand).

The growth of VRE in Europe by 2030 will entail an overall increase in flexibility needs, especially for daily flexibility resources: 2.4-fold growth in daily, 1.8-fold in weekly and 1.3-fold in annual flexibility needs

Using the methodology from **(EC, 2019h)**, this report estimates flexibility needs represented by daily, weekly, and annual flexibility needs. These shall be understood as the variations of residual demand within the time indicated scopes. Daily flexibility needs present how much residual demand varies hourly with respect to the daily average of hourly residual demand. Weekly flexibility needs refer to the variation of daily residual demand with respect to its weekly average. Lastly, annual flexibility needs represent the variation of monthly residual demand to the annual average residual demand.

These three different time scopes capture the different fluctuations or cycles of demand and VRE generation. Daily flexibility captures daily patterns of demand (morning and evening peaks, night valleys) and the solar cycle (no generation at night, peak at midday hours). Weekly flexibility is mostly driven by wind regimes and weekday/weekends. Finally, annual flexibility covers seasonal patterns of wind generation (higher in winter, lower in summer), solar generation (lower in winter, higher in summer), and demand (depending on heating and cooling demand over the year).

The average daily, weekly and annual flexibility needs in the period 2015-2021 were 157 TWh, 128 TWh and 130 TWh respectively. In 2030, with a projected VRE installed capacity 3.4 times higher than in 2021, there is a consequent growth in flexibility needs.

This report estimates the flexibility needs for the scenario with existing and planned interconnectors and reference demand projection to be 362 TWh, 242 TWh, and 168 TWh for daily, weekly and annual flexibility needs. This means an increase of 138%, 77% and 28% in daily, weekly and annual flexibility needs compared to the situation in 2021.

As in **(EC, 2019h)**, this report finds a steep increase in flexibility needs towards 2030, especially on a daily basis. Therefore, it is necessary to assess whether the European electricity system has sufficient flexibility resources to ensure that the system can cope with short, medium and long-term fluctuations of VRE generation and inflexible demand (not all demand can be fully flexible) and fully exploit all flexibility resources available in the system that may not be actively participating today (e.g. demand response).

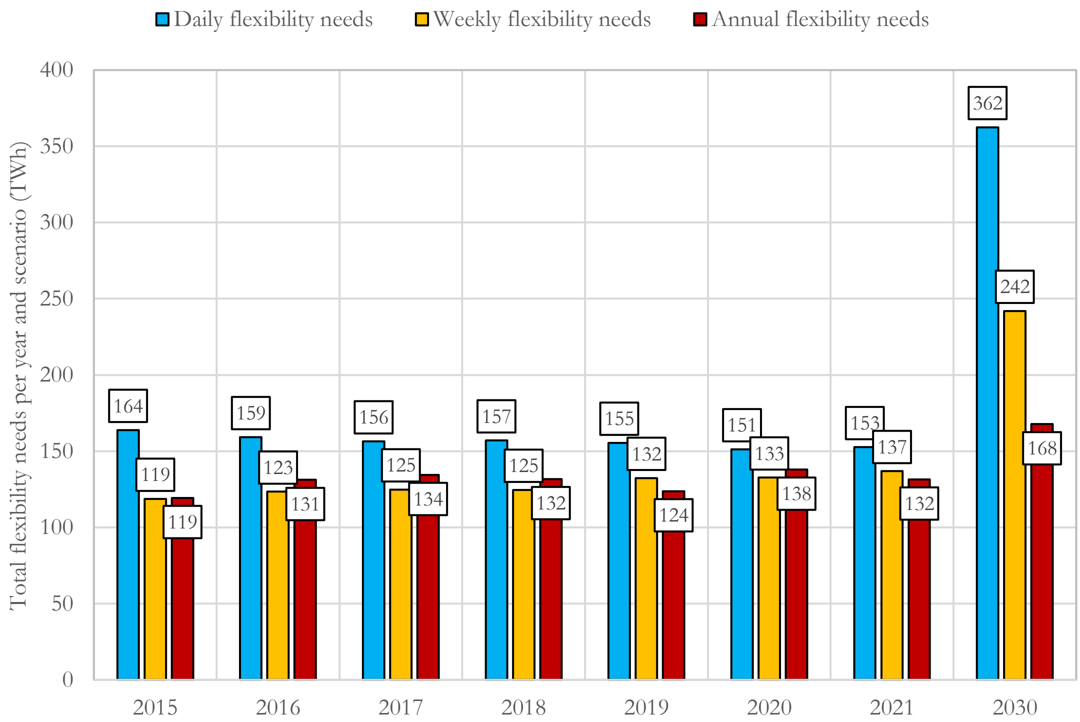

Figure 3-21. Daily, weekly, and annual flexibility needs per year in Europe.

Sources: Hourly generation and demand data from ENTSOE transparency platform **(ENTSO-E, 2022d)** ; 2030 annual projections from the Policy scenarios for delivering the European Green Deal **(EC, 2021e).** combined with historic hourly profiles from **(ENTSO-E, 2022d)**.

Notes: 2030 results correspond to the average simulation results under the scenarios considering existing and planned interconnectors and no demand savings and shifting measures.

Existing and planned interconnectors lead to an overall decrease in daily, weekly, and annual flexibility needs of 3, 30 and 15 TWh in 2030 for all European countries scoped in this work.

The net effect of existing and planned interconnectors in Europe is an overall decrease of daily flexibility needs of 3 TWh (1% of daily flexibility needs without interconnectors), an overall decrease in weekly flexibility needs of 30 TWh (12% of needs without interconnectors) and a decrease in annual flexibility needs of 15 TWh (9% of needs without interconnectors). See middle bars on Figure 3-22.

Detailed impacts for successive interconnection levels can be found on Figure 3-22. The effect of an unlimited interconnection capacity in Europe leads to a significantly higher decrease in flexibility needs: 7 times lower than the reduction with existing and planned interconnectors for daily flexibility needs and more than 3 times lower for weekly and annual flexibility needs.

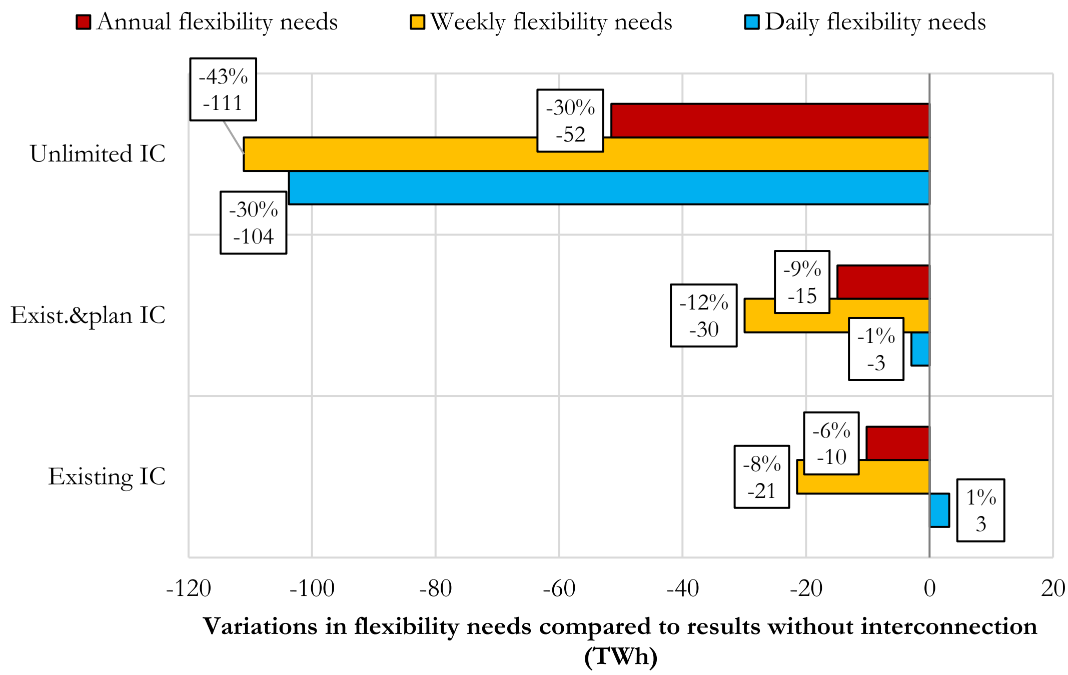

Figure 3-22. The value of cross-border interconnectors and demands-side measures applied in reducing flexibility needs.

Sources: Hourly generation and demand data from ENTSOE transparency platform **(ENTSO-E, 2022d)** ; 2030 annual projections from the Policy scenarios for delivering the European Green Deal **(EC, 2021e).** combined with historic hourly profiles from **(ENTSO-E, 2022d)**.

Notes: The bars represent changes in daily, weekly, and annual flexibility needs for successive interconnection levels compared to average results without interconnection. Values correspond to averages of all simulations performed per interconnection scenario.

Nevertheless, there is still a high need for other flexibility resources even under a scenario of unlimited interconnectors: 249 TWh for daily flexibility needs, 157 for weekly, and 129 for annual flexibility needs. For unlimited interconnection capacity, the two latter are found around similar levels to flexibility needs in 2021, pointing at a greater weekly and monthly complementarity in European VRE generation and demand profiles than at a daily level.

Therefore, other flexibility resource types than cross-border transmission capacity must be operative in the system to face fluctuations that cannot be solved with interconnectors.

Two recent reports, (Koolen, D., De Felice, M. and Busch, S., 2023) and (Trinomics and Artelys, 2023), have also analysed flexibility needs and the flexibility value of interconnectors. While using a similar metric for flexibility as the one used in this report, originally defined in (EC, 2019h), the results for the flexibility contribution of interconnectors vary between reports.

For example, the contribution of interconnectors to daily flexibility in Germany by 2030 is found in (Trinomics and Artelys, 2023) to be around 45% in the Stated Policy change scenario, around 35% in the technology driven scenario, and 20% in the system change scenario. (Koolen, D., De Felice, M. and Busch, S., 2023) finds however a contribution from interconnectors to daily flexibility needs in Germany in 2030 of around 6%. Our analysis shows a lower value of interconnectors to flexibility needs (1% lower for daily flexibility needs compared to a scenario without interconnectors), but this percentage is not directly comparable as it refers to a different calculation concept.

The decrease in this report refers to the difference of residual demand variations achieved under scenarios without and with interconnectors. In the JRC report, the contribution of interconnectors refers to the change in residual demand variation when one subtracts the net exchanges in the interconnectors from the original residual demand. Yet, all reports conclude a positive contribution of interconnectors to flexibility.

It must also be highlighted that this analysis finds a slight increase in daily flexibility needs in the scenario with existing interconnectors compared to the scenario without interconnectors. This can be observed in the small positive blue bar on Figure 3-22. This effect of interconnectors to residual demand variability was also found in (EC, 2019h), where they found that while interconnectors can provide flexibility to some Member States, they may increase flexibility needs in others[31].

An illustrative example of the exchange of electricity between Spain and France for one specific week is given on Figure 3-23. Here, it is shown that the overall residual demand variability is increased with the interconnector, and thus, given the flexibility needs metric, flexibility needs are slightly higher with the interconnection than without it. The effect is only found for daily flexibility needs. For weekly and annual flexibility needs, the aggregation of residual demands over less granular time horizons seems to cancel this negative result.

As it can be observed on Figure 3-23 (top chart), in the first three days of the week there is an exchange of VRE excess from Spain to France. The effect of the trade is an upward shift of the Spanish residual demand curve and a downward shift of the French residual demand curve (by the same amount of electricity exchanged). In the Spanish case, the new residual demand is closer to the daily average and thus the flexibility needs are decreased (Figure 3-23, bottom left chart). On the other hand, in France, the new residual demand profile is more deviated from the daily average and daily flexibility needs are increased (Figure 3-23, bottom right chart).

[31] (EC, 2019h), page 67.

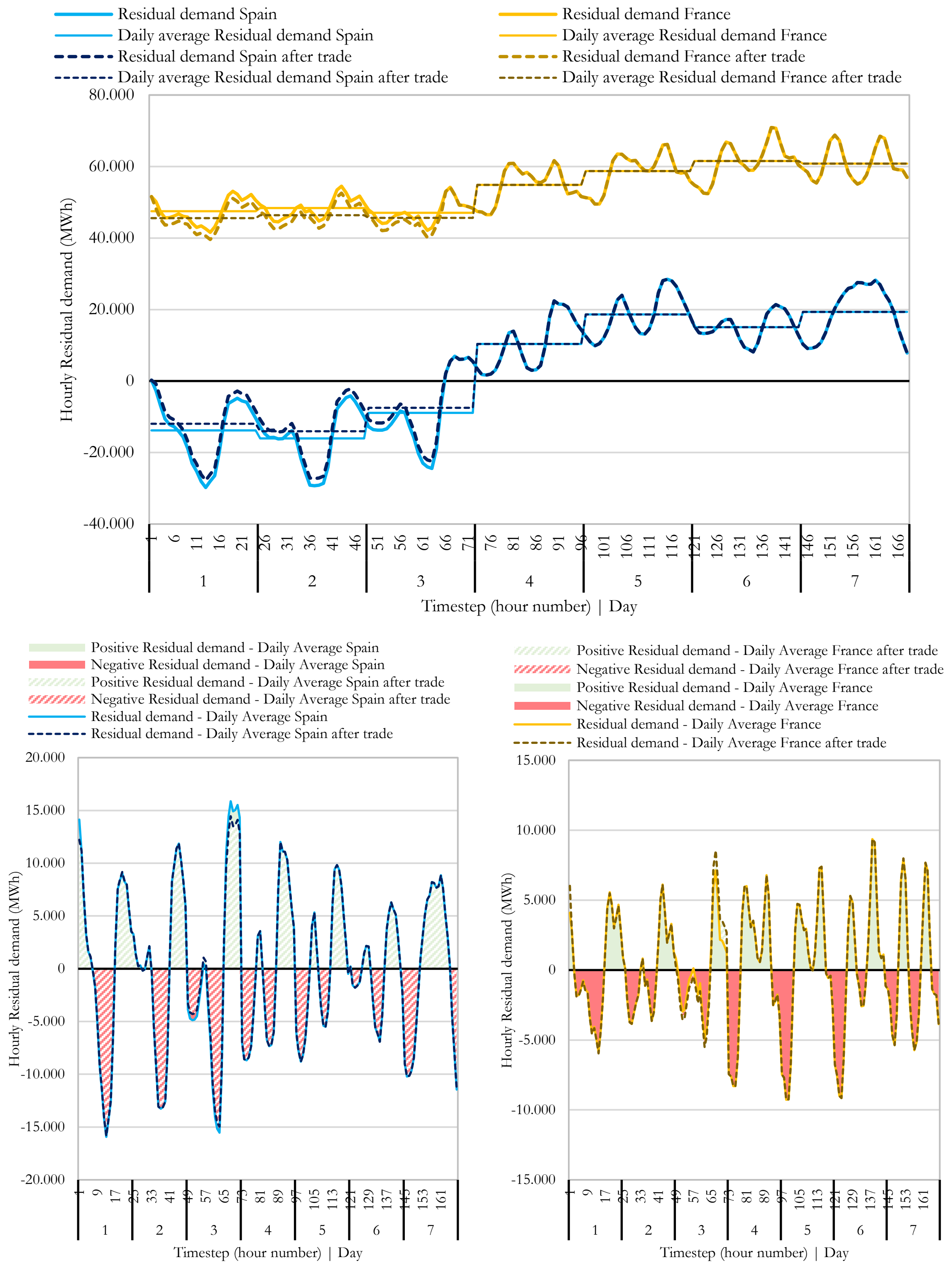

Figure 3-23. Illustrative example of negative flexibility contribution from interconnectors in Spain and France for a specific week.

Notes: Top: Residual demand in Spain and France and daily average residual demands before and after cross-border exchange. Bottom left: daily flexibility needs in Spain before and after cross-border exchange. Bottom right: daily flexibility needs in France before and after cross-border exchange.

Demand savings and shifting applied in this report result in a reduction of daily, weekly and annual flexibility needs by 2030

Figure 3-24 show the contribution to flexibility from demand savings and demand shifting measures as an example of how an overall demand change (10% savings in non-peak hours without VRE excess and 5% in peak-hours with potential shifting to VRE excess hours) can decrease flexibility needs in the system.

The contribution of demand response measures to flexibility is estimated as the difference in the flexibility needs metric (variability of residual demand) between the simulation results with and without the demand response measures.

The contribution entails reductions in flexibility needs of 7% (24 TWh) for daily flexibility needs, 9% (21 TWh) for weekly flexibility needs, and 12% (19 TWh) for annual flexibility needs, compared to the corresponding results using the reference demand.

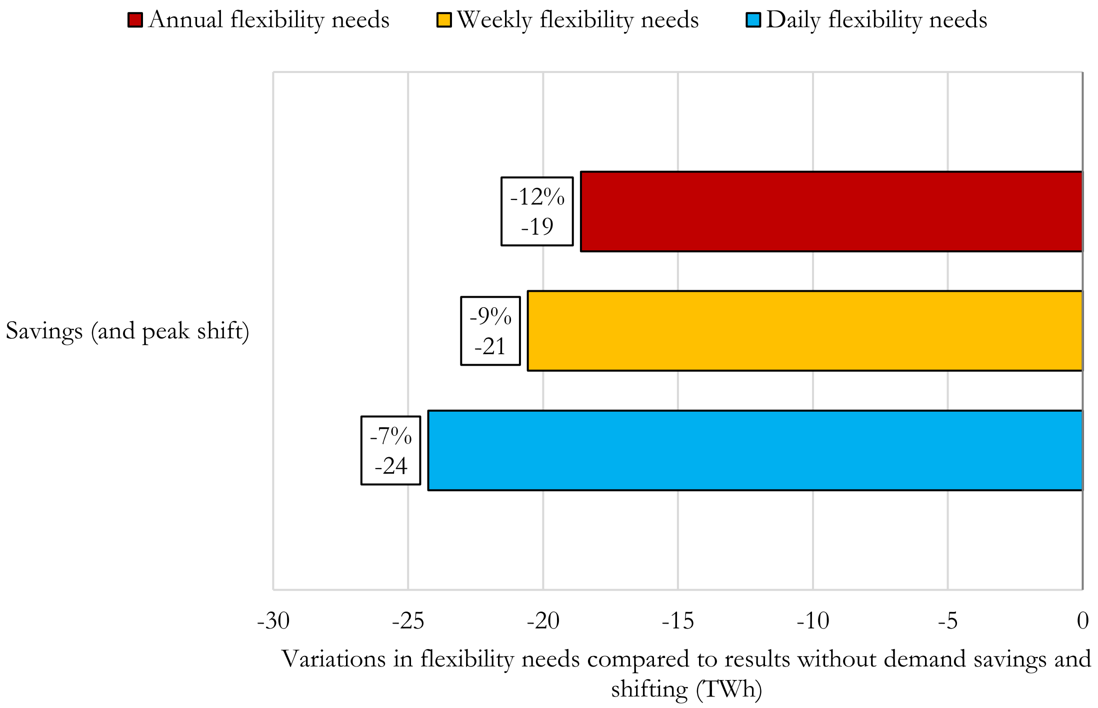

Figure 3-24. The value of demand-side measures applied in reducing flexibility needs.

Sources: Hourly generation and demand data from ENTSOE transparency platform **(ENTSO-E, 2022d)** ; 2030 annual projections from the Policy scenarios for delivering the European Green Deal **(EC, 2021e).** combined with historic hourly profiles from **(ENTSO-E, 2022d)**.

Notes: The bars represent changes in daily, weekly, and annual flexibility needs for demand savings and shifting compared to average results with the reference demand. Values correspond to averages of all simulations performed per demand scenario.

4 Case studies

4.1 Case Study 1: Hybrid energy park

Case Study: Haringvliet Hybrid Energy Park (HHEP)

Main Hypothesis: Hybrid renewable energy parks with storage assets have the potential to enhance the flexibility of variable renewable energy sources (VREs) by reducing periods of VRE excess and deficit.

Summary

HHEP is an innovative project that combines wind turbines, solar panels, and battery storage to improve assimilation of renewable energy into the grid. All installations share a common grid connection, which is expected to contribute to grid stability through battery storage and frequency control. HHEP is the first hybrid park in Europe that integrates solar, wind, and battery storage into a common grid connection.

Key Takeaways:

- Hybrid renewable energy parks that combine different technologies, in this case wind, solar and batteries, have the potential to increase the amount of production hours due to the diversity of the renewable energy production units in a single point.
- Combining different renewable energy technologies in a hybrid energy park improves efficiency not only for the grid, but also in terms of scale effects. The increased production based on the different technologies leads to a higher utilization rate, and thus a higher efficiency, of the substation equipment per unit of energy produced.

Figure 4-1: Haringvliet Zuid Energy Park. Source: Vattenfall

Project Description & Overall Objectives

Vattenfall's HHEP is a renewable generation and storage project that operates since 2020. It aims to demonstrate advantages in terms of cost-effectiveness and reliability from the synergistic integration of complementary VRE sources and chemical storage. The project is located on Goeree-Overflakkee, an island 20 kilometres south of Rotterdam in the Netherlands. The project integrates 38 MW of solar PV, 22 MW of onshore wind turbines, and 12 MW of battery electric storage system (BESS; 288 battery modules). The park is expected to offset 50,000t of CO_2 and provide electricity to 12,000 households (Pombo et al., 2021).

The batteries help balance the grid on a local level, and shared facilities such as the substation, cables, and grid connection save maintenance time, reduce costs, and have a smaller environmental impact than individual connections. Key benefits of the HHEP project include optimizing electricity production through the combination of different VRE technologies and storage capabilities, providing a more constant electricity supply, and involving the community in the design and development of the park.

The involvement of the community living on the island in the vicinity of the project area was crucial in achieving public acceptance for the project. By including the community in the design process, the project was planned and implemented in an environmentally considerate and publicly acceptable manner. Small details, such as including bicycle lanes around the park, helped the project contribute to creating a sustainable and liveable community. The limit on the height of the PVs, set at 1.5 meters, is another feature of how the project aimed to minimize its impact on the landscape.

Despite most project developers focusing on single technology sites, rather than integrated technology sites, the HHEP stakeholders and developers see the HHEP project as a blueprint for future hybrid energy parks.

Challenges

- Due to the complex nature of the project, several initiatives were necessary to introduce a hybrid energy park in early 2010 and to secure permits for its distinctive components: the solar, battery, and wind turbines. Several challenges related primarily to the combination of different technologies. For instance, the subsidy design was mainly intended to support solar power generation, yet not wind generation.

- After winning the tender for developing the hybrid energy park, Vattenfall's initial objective was to maximize the number of wind turbines installed on the site. However, the dialogue with multiple stakeholders, such as the landowner, the grid owner, and the municipality, raised different viewpoints that had to be considered. Nevertheless, since the project was considered a pilot for hybrid production and energy storage, legal complexities were reduced, and the permit was granted relatively quickly.

- As a pilot project for hybrid technologies, HHEP was able to receive support, even though the Netherlands has no specific policies to encourage hybrid energy parks. Challenges however were the required coordination of interfaces between the three technologies involved. To merge all three technologies and their interfaces, contracts for the installation of the wind farm, solar panels, and battery system had to be carefully coordinated between several institutions. This complexity made the construction process challenging, and there were also challenges in terms of integrating the production profile of each technology to ensure optimal performance of the entire system.

- Renewable energy project developers in the Netherlands face a challenge regarding zoning regulations, as agricultural lands can typically not be converted to large-scale wind and solar farms. While it may be possible to achieve local targets for renewable energy with small-scale wind or solar farms, this strategy may not be sufficiently comprehensive for the energy transition; an integrated energy landscape combining renewable energy with residential and agricultural areas could be more efficient and effective to sustain success across all sectors.

- More generally, few energy projects to date have followed the example of integrated technologies demonstrated by the HHEP. Challenges to construct single technology parks are relatively low, compared to hybrid parks, which require careful coordination and adjustment of multiple technologies and energy storage systems. In turn, a lack of hybrid energy parks presents a challenge in convincing other competent authorities to support development of hybrid energy parks. Synchronizing the different activities related to the construction of hybrid parks can also be more resource-intensive for local and regional authorities. The absence of specific national policies enabling the development of hybrid energy parks adds further to these challenges.

Business case

The HHEP benefits from the operational flexibility provided by the combination of wind, solar, and battery systems, which allows it to generate multiple revenue streams, enhancing the overall economic viability of the project. In addition to providing renewable energy to the grid, the park can participate in balancing markets to provide additional value[32]. Namely, the battery system is primarily used for providing Frequency Containment Reserve (FCR), which helps to maintain the frequency stability of the grid.

The Battery Energy Storage System (BESS) plays a crucial role in supporting the grid by providing reserve capacity that can be utilized to balance power supply and demand during periods of frequency deviations. In addition to addressing curtailments caused by grid congestions, the BESS also provides a more flexible and responsive operation to grid needs (Pombo et al., 2021). The successful qualification of the battery for FCR provision has opened opportunities for the HHEP to participate in additional balancing services in the future, which can further increase its profitability.

During the development phase, a government subsidy aimed at improving security of supply in the energy sector was a major driver for the project. Moreover, the Dutch government had set targets for wind power generation, and each province in the country was allocated a portion of the national target. This combination of incentives and targets helped to create a favourable environment for the development of the HHEP.

[32] The Dutch TSO, Tennet, allows the participation of battery storage systems in balancing markets, but this is not the case in all EU countries today.

Decarbonisation Relevance – Contribution to climate goals

The HHEP has successfully achieved its project objectives, meeting the expected levels of electricity production and GHG emissions reduction. The park generates renewable electricity that can power up to 40,000 households per year, based on an average annual consumption of 2,500 kWh per household.

In addition to electricity generation, the park has also contributed to a significant reduction in CO_2 emissions, estimated to be around 40 kton per year[33], which demonstrates the positive contribution of the project to climate mitigation.

Lessons Learned

To accelerate the development of hybrid energy projects like HHEP, it is essential to establish stronger political support both at the national and EU level. In the case of HHEP, the absence of enabling policies presented a significant barrier to its development. However, the Dutch sustainable energy transition subsidy scheme (SDE) aimed at ensuring security of supply provided additional subsidies for the project, which helped overcome this challenge.

For future hybrid energy parks to succeed, robust political support and specific requirements, such as related to security of supply, are needed. Without such support, project developers are likely to focus on single-technology sites, due to the complexity of technology and permitting issues. Therefore, additional policies and regulations seem necessary to encourage the development of hybrid projects that can maximise benefits in terms of electricity production, environmental and GHG impact reduction, and operation flexibility.

Despite these challenges, the success of the HHEP demonstrates the potential for future projects to integrate multiple clean energy resources to achieve reliable and economic energy production.

[33] The estimate is assuming an average emission factor of 110 kg CO_2/GJ of electricity production.

4.2 Case Study 2: Hybrid interconnection

Case Study: Kriegers Flak Combined Grid Solution (KFCGS)

Main hypothesis: There will be a RES generation boost, improved flexibility, and supply adequacy improvement through cooperation between European Member States using innovative cross-border interconnectors.

Summary: Kriegers Flak Combined Grid Solution is the world's first combined solution of offshore wind connection and interconnection of countries in one integrated solution. The project allows wind power plants to trade electricity in an integrated infrastructure. By full utilisation of the wind generation potential and enhanced interconnection capacities, the project has significant socio-economic value.

Key Takeaways:

- System and market integration enhance decarbonisation, as markets can attract more sustainable investments and facilitate the exploitation of economies of scale.
- Due to the geographic diversity of Europe, certain Member States are better endowed to produce certain types of renewable energy at scale and at lower costs. For example, offshore wind from the North Sea has the potential to power a major part of industries of continental Europe and has lower costs than developing offshore wind in other sea basins with higher depths.
- This diversity provides for competitive advantages when sharing renewable energy cross-border.
- Mutually beneficial sharing of resources is made possible via Europe`s integrated power system supported by its physical and market integration and the common rules and standards behind them.

Figure 4-2: Kriegers Flak. Source: 50 Hertz

Project Description & Overall Objectives

Kriegers Flak has a capacity of 604 MW acting as a supergrid, supplying renewable electricity to the two countries' power grids (Power Technology, 2022). The construction of KFCGS began in 2016 and the interconnector has been in operation since December 2020. The collaboration between the German and the Danish transmission system operators 50Hertz and Energinet enabled the conception of the world's first hybrid offshore wind interconnection, that is, a dual-purpose transmission infrastructure solution to connect both markets and bring offshore wind power to the shore. This was done by using the national grid connections of two wind farms that are 30 kilometres apart, the Denmark's Kriegers Flak and Germany's Baltic 2. The two wind farms are connected by two underwater cables that have a transmission capacity of 400 MW and connect the Zealand region in Denmark with Mecklenburg-Western Pomerania in Germany, allowing electricity trading in both directions (Energistyrelsen and Naturstyrelsen, 2015).

In 2014, the project (budgeted at €1 billion) became a European pilot project and a model for future offshore wind farms in the North Sea, the Baltic Sea, and the Mediterranean. KFCGS was the first project aiming at transnational large-scale interconnections (OffshoreWIND.biz, 2014). The project required stakeholders at several levels, including project developers, policy makers, and energy regulators (Power Technology, 2022). The appropriate and comprehensive integration of cross border transmission infrastructure and offshore wind energy farms required the adjustment of existing regulation and the creation of updated regulatory initiatives at a variety of levels, regional, national, and international.

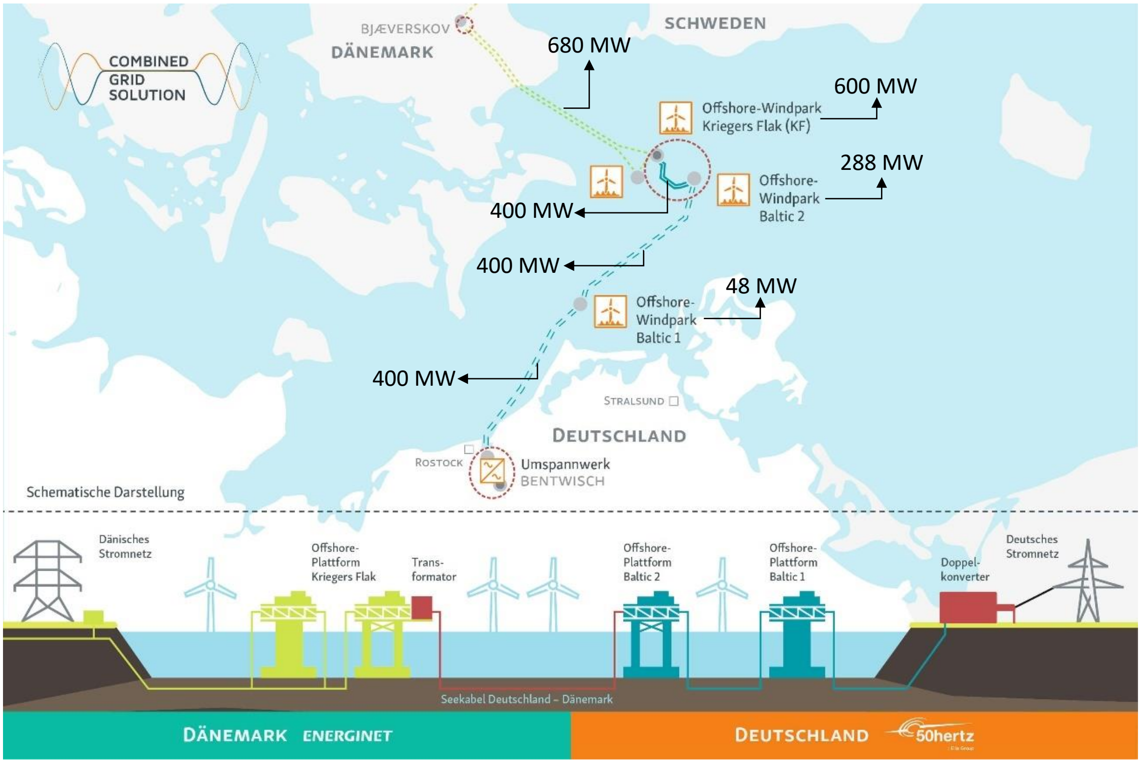

Figure 4-3: Kriegers Flak location and connection. Source: (WindFair, 2020). Power capacities indicated from (REF).

Challenges

The main types of challenges in the KFCGS project related to the technical infrastructure, environmental challenges (e.g., different phases in transmission), challenges related to interaction between two TSOs from two countries, and challenges linked to the pilot nature of the project itself.

Germany and Denmark represent two different bidding zones, subject to price differences, and two market operators, Nord Pool Spot and European Energy Exchange (EEX), active in both bidding zones (NordPool, 2020). Furthermore, each of the countries also has different support schemes for renewable energy sources. Often, the energy markets alone do not provide enough incentives for the development and deployment of renewable energy sources of such scale. When this is the case, government support is necessary to overcome this market failure and encourage investment in these technologies. With the Renewable Energy Directive 2009/28/EC, Member States have the possibility to decide whether and how to support renewable energy projects in other EU countries. The recent Electricity Market Design proposal (EC, 2023b) defines new rules for RES support schemes, as the only allowed support scheme will be two-sided CfD schemes. Another challenge faced by KFCGS is the geographical location. The Baltic area has extremely irregular soil conditions with differently sized boulders both under and above the ocean (OffshoreWIND, 2022).

Other challenges concerned government permits and legal aspects. Specifically, securing the needed permits and the electricity grid connection on land were prerequisites for completing the offshore wind farms. Legal challenges were generally resulting from the incompatibility between national laws of the different countries. Both Germany and Denmark have different grid infrastructure laws and treatments thereof.

One specific challenge thereof – with relevance for other offshore wind farms

Regulation (EU) 943/2019, which came into force shortly before the commissioning of KFCGS, requires TSOs to allocate 70% of any cross-border interconnection capacity for cross-zonal trading and to not limit the volume of interconnection capacity available to market participants to solve congestion inside their own bidding zone, or to manage flows resulting from transactions within bidding zones. The rationale of these requirements for cross-zonal trade is to ensure the integration of electricity markets in the European internal market as a key to delivering Europe's energy goals (ACER, 2020). In the specific case of KFCGS, however, the main goal of the interconnector linking the two offshore wind farms from different countries was to increase the use of the connections between the wind farms and their respective onshore grids by making available this capacity for cross-zonal trade when it was not fully required for transporting electricity generated from the wind farms to shore (EC, 2020e). The 70% minimum requirement could have posed challenges to the business case of the KFCGS project: the available transmission capacity from the wind farms (Kriegers Flak in Eastern Denmark, bidding zone DK2, and Baltic 1 and 2 in Germany, bidding zone DE) to their respective bidding zones could have been reduced in practice to free up capacity for cross-border trade between DK2 and DE. The Danish and German authorities requested that the 70% requirement was calculated over the remaining capacity left by the offshore wind farms output.

To address this issue, the European Commission granted a derogation to KFCGS from the respective provisions of the Regulation, as compromise solution to mitigate negative effects of KFCGS' business case due to a change in regulation during the project execution. Nonetheless, the derogation means priority access to the interconnector by the offshore wind farms and thus generates discrimination against other generation sources from both sides of the KFCGS interconnector. The derogation can result in a less efficient market outcome when other generation sources, land-based or from other offshore wind farms have a lower cost than the offshore wind farms connected by KFCGS.

The market configuration for the integration of the future offshore energy systems (offshore wind targets of at least 60 GW by 2030 and 300 GW by 2050 (EC, 2020c)) is still under consideration in the EU. KFCGS is today the only existing hybrid interconnection project, but more projects like KFCGS are expected in the future as hybrid offshore interconnectors can bring substantial socioeconomic welfare improvements by allowing increased market integration, more coordinated investments, a decrease in system costs and a lower need for additional connection points and thereby a more limited impact on the environment than when radial connections are used (EC, 2022o).

From an economic and regulatory perspective, it is generally agreed that dedicated offshore bidding zones can be the most efficient solution to integrate hybrid offshore wind interconnection projects in the European electricity system as they provide the most granular representation of the grid in the market clearing (ENTSO-E, 2020), (ACER and CEER, 2022), (EC DG ENER, 2020), (EC, 2022o). Conversely, the traditional market approach of home market zones, where offshore wind farms belong to their closest land bidding zone (as in KFCGS) make the connection to land invisible to the market and potentially create a need for redispatch or countertrading measures.

Offshore bidding zones can also constitute a wide range of challenges that need further consideration not covered in this report (ACER and CEER, 2022).

Decarbonisation Relevance – Contribution to climate goals

The main objectives of the project are in line with promoting better assimilation of the growing share of renewable electricity sources and maintaining security of supply, while bringing renewable energy to European consumers in Germany and Denmark. More specifically, KFCGS contributes to decarbonisation by reducing GHG emissions, compared to conventional power production by an expected 325 kton CO_2 every year. As a reference, Denmark had a yearly emission of 29,700 kt of CO_2 in 2019 (The World Bank, 2020). The project's long-term plans therefore support Denmark's and Germany's energy policy goals regarding energy supply security and development of renewable electricity by 2050.

Security of Supply Relevance

The Baltic Sea region has high potential for wind energy generation due to its strong and consistent wind conditions. The use of wind power in the Baltic region can therefore help increase the security of energy supply. KFCGS is being used in this manner, increasing the security of energy supply in the Baltic region. Through the existing interconnector, KFCGS sends up to 1000 MW of electricity between the Danish and German power grids, ensuring a more stable and reliable supply of electricity, even when wind conditions are poor in one area. The KFCGS has further advantages regarding security of supply, which comes from the additional transmission capacity between the two connected countries. Therefore, up to 1000 MW of power could be transferred without reinforcements, and this is relevant when looking at the improved security of supply in the eastern Denmark region (Energinet et al., 2009)

Lessons Learned

The case illustrates how offshore hybrid systems promote both RES and market integration by serving as dual connection purposes for offshore wind farms and bidding zones. Therefore, they contribute to the objectives of decarbonisation and security of supply. Offshore hybrid interconnection projects result in substantial socioeconomic welfare improvements by allowing an increase in market integration, a more coordinated investment planning and a decrease in system costs. The cross-border interconnection of offshore wind farms in hybrid systems lowers the need for other cross-border interconnection points and limits accordingly the environment impacts normally associated with traditional radial connections from offshore wind parks to shore.

A proper framework guaranteeing investment stability and certainty is a prerequisite for offshore investments. The recent Electricity Market Design proposal (EC, 2023b) by the Commission includes transmission access guarantees for offshore wind farms to the cross-border transmission capacity of hybrid systems. If the available transmission capacities are reduced to the extent that the full amount of electricity generation by the offshore project cannot be delivered to the market, the TSOs can compensate the offshore project operator using congestion income (EC, 2023d).

In the case of KFCGS, several policies contributed to the realization of the project. Specifically, global and European climate change policies, as well as EU and national renewable energy targets and Danish and German renewable support schemes. The European cross-border trade in electricity too was a supporting factor for this project. In 2015, the European Commission proposed KFCGS to be a Project of Common Interest (PCI), the project thereby receiving financial support of up to 48.2% of its total costs (€150 million) from the European Energy Programme for Recovery (EC, 2020a)[34]. The PCI status identified KFCGS as a priority for the EU and gave the project a higher level of visibility and political support, helping promoters to secure funding and facilitating the implementation of the project by ensuring that the project is in line with the EU's energy and climate goals.

KFCGS is a pilot project that helped to identify important issues related to cross-border energy cooperation, specifically, the need for effective coordination and approval between the reciprocal laws, regulations, authorities, and institutions of the countries in question, the need for regulatory coordination and innovation, and the importance of political support and commitment from the regional, national, and European governments. Political support was also important in terms of navigating the legal and regulatory frameworks that governed the project. The project required the approval of various authorities, including the Danish and German governments, and the EU, which would have been greatly facilitated by the support of political decision makers.

[34] The European Energy Programme for Recovery was a European regulation that began in 2008 to help energy policy objectives after the financial crisis, to fund projects in specific areas of the energy sectors, among other offshore wing energy.

4.3 Case Study 3: Demand response from heating systems

Case Study: Heat Smart Orkney (HSO)

Main Hypothesis: The electrification of end-uses via smart sector integration, supported by energy production co-optimisation, allows a more secure and cost-effective integration of VRE sources in support of decarbonisation goals.

Heat pumps and electric boilers when able to receive grid operator signals can be used as a demand response measure to help reduce the potential curtailment of VRE and increase flexibility on the grid by allowing decentralized users to participate in energy markets. The integration is equally relevant when communities use district heating. In such cases, the flexibility of the district heating system can be even higher as thermal energy storage and alternative heat sources can be used optimally. The optimal coupling between VRE sources and thermal grids – both heating and cooling – can increase security of supply if done correctly.

Summary Description:

Heat Smart Orkney (HSO) was a community-led renewable energy project located in Orkney, Scotland. Although the project does not lie within the European Union anymore, it is interesting to assess as the idea could also work within the EU. The project was running in different development phases from 2016-2020 and then moved into a commercial phase. In the following we will describe the learnings from the second development phase. The project aimed to address the curtailment of electricity production from community-owned wind turbines through demand side management by installing electric heating devices in homes all connected to a central control platform.

Orkney Islands faced a grid congestion problem due to the connection of successive new wind turbines since 2000 without a parallel grid reinforcement, notably at the interconnector joining the islands with mainland Scotland. To meet this challenge, the HSO project examined the potential to use hot water immersion heaters and stand-alone intelligent electric heaters with controllers to use excessive wind power (which could not be transported to the mainland) and hence reduce curtailment. The project only focused on one 900-kW community scale wind turbine on the islands of Rousay.

Heating devices were installed on 72 properties. Each heating device installed can consume up to 2.3 kW. With 108 electric heaters and water immersion heaters installed in the 72 households, this amounts to around 250 kW. The heating devices were activated in periods with high VRE production from the local wind turbine to absorb electricity that would otherwise be curtailed. During imminent curtailment events, a signal from the turbine operator was sent to heating devices to switch on. This activated them to absorb otherwise curtailed electricity and increase generation payments to the community-owned turbine, while supplying secondary heating to homes.

The project serves as an example of how communities can take action to address local congestion problems in the electricity grid and better utilize VRE sources. The project also shows that for a heating system to provide flexibility to an electricity system, more than one heat source is required. Either via a flexible boiler-electric heating solution in households (as in this case study) or through a district heating system with multiple heat sources and thermal storage.

To make the idea a viable business case more consumers and producers must be connected to the platform. The cost break-even is expected to be around 800 heating devices and 5 wind turbines, something which the project is currently seeking to do in its commercial phase.

Key project takeaways:

- The project showed that it is possible to reduce the impact of local grid constraints by utilizing otherwise curtailed electricity from wind turbines for local heat production.
- The HSO project demonstrated that technologies can be brought together to intelligently control electrical demand in response to the onset of turbine curtailment. The project uses real-time data from a commissioned wind turbine connected to an active network management system and quantifies the level of intervention required to reduce wind turbine curtailment.
- The project also indicates that other measures than individual heating devices will complementarily help integrate VRE sources at a large scale, as the volumes of otherwise curtailed electricity generation only covered 1 % of the total heat demand of the buildings connected to the project. Emission reductions and the reduction in wind curtailment levels are likewise marginal compared to annual production numbers.

Project Description & Overall Objectives

The Orkney Islands (Orkney) are a remote archipelago off the Northern Coast of Scotland with a population of roughly 22,000 people spread over 20 inhabited islands. Located on the Orkney Islands are 23 wind turbines which regularly deliver more than 100% of the island electricity demand. Although the Orkneys are linked to the mainland by an undersea electric cable, the production from the wind turbines is often curtailed, as the export cable is constrained.

The Heat Smart Orkney (HSO) project was a community-scale pilot project developed to reduce the curtailment of the island of Rousay´s wind power generator. The 900-kW wind turbine produces around 2.5 GWh per year. Total wind turbine electricity production on the Orkney Islands is approximately 180 GWh/a, so the pilot project only covers 1.5 % of the island’s electricity production from wind. The project does not cover the entire Orkney Island wind turbine fleet, but only one.

Annually, around 30 % of the wind turbine’s production on Rousay – 0.7 GWh – gets curtailed. Around £ 110,000 in revenues get lost. To reduce the amount of wind curtailment, the HSO project sought to install electric heating devices connected to a central control unit in the houses on the island of Rousay. The heating devices were activated by an active network management system, which used an algorithm to predict periods of curtailment and heating loads.

The heating devices were activated to absorb otherwise curtailed wind production in exchange for payments from the turbine operator. Households that participated in the project received a £150 incentive upfront in addition to rebate payments of 6p/kWh consumed electricity that would have otherwise been curtailed. The wind producer in average earned 16p/kWh in the electricity market between 2016 and 2020. Giving 6p/kWh to the consumer reduced the received earnings to 10 p/kWh but must be seen in the light that the production would otherwise have been curtailed at no payment. The income from marginal wind turbine production was therefore allocated between producers and consumers.

Yet, the overall reason the scheme could be operated was due to the grants provided to run the pilot phase. A scale-up of the number of heating devices and wind turbines connected are needed for the commercial phase to be profitable. The pilot project was operated from 2017 to 2019, albeit that the project was running in different development phases from 2016-2020, and then moved into a commercial phase.

Because the heating devices were only activated when a marginal curtailment event occurred, the operation time was rather limited. The results from the operation of the pilot project in 2018 and 2019 can be seen in Table 4-1. Marginal curtailment is when the turbine is kept in operation but reduced in output. A full curtailment event shuts down the turbine. It is only during marginal curtailment that the heating devices are in operation to keep the wind turbine in operation at a higher set-point. The load dispatch of the heating devices can also be seen. Most of the operation is to match curtailment, yet due to flaws in the control signalling, but also due to heating demand, the heating devices were also kept in operation after the marginal curtailment event (overspill) and in periods with no curtailment (other load).

Table 4-1: Total production, curtailment, and load dispatch (heating devices)

Concept	2018	2019
Annual electricity production at wind turbine	**2,450 MWh**	**1,950 MWh**
Not curtailed production	2,009 MWh	1,774 MWh
Curtailed production	343 MWh	137 MWh
Marginal curtailment	**98 MWh**	**39 MWh**
• Mitigated curtailment	15 MWh (15 %)	3 MWh (8 %)
• Undetected marginal curtailment	18 MWh (18 %)	19 MWh (49 %)
• Detected but not mitigated	65 MWh (66 %)	17 MWh (44 %)
Load dispatch (heat devices)	**20.5 MWh**	**6.6 MWh**
• Matching curtailment	15 MWh (73 %)	3.3 MWh (50 %)
• Overspill	1.5 MWh (7 %)	0.3 MWh (5 %)
• Other load	4 MWh (20 %)	3 MWh (45 %)

HSO was led by Rousday Eglisay & Wyre Development Trust (REWDT) through its project-specific subsidiary Heat Smart Orkney. Additional project partners included Rousay Egilsay & Wyre Islands Renewable Energy Development (REWIRED), Community Energy Scotland (CES) VCharge (Kaluza), Catalyst and other Orkney-based development Trusts (Compton and Hull, 2022b). The project was funded by the Scottish Governments Local Energy Challenge Fund and the EU's Horizon 2020 funds.

- The project required relatively limited resource inputs as the turbines existed. Costs mainly related to software development, IT support, and installation and maintenance costs of the heating devices and smart devices which connected the heating devices to a controller platform.

Challenges

Market Challenges

- **Attracting new turbines to join the HSO scheme:** The project experienced challenges generating interest from other wind turbine owners and new collaborations, due to required agreement to existing rebate structures. It would first be after five turbines have joined the scheme that profitable operation is expected.
- **Attracting new households to join the HSO scheme:** The project experienced challenges attracting households beyond the islands of Rousay, Egilsay and Wyre, for which HSO Ltd. has less experience through the trial to-date and has fewer existing community networks. The project is very locally integrated.
- **Securing investment to scale:** Challenges associated with securing the investment required to scale the HSO scheme - particularly, in the initial scale-up stages before the scheme is profitable has been a challenge.

Technical Challenges

- **Unforeseen communication issues:** The issues caused the curtailment efficiency to decrease as significant curtailment was experienced but not communicated between systems of the wind turbine and the heating devices. Improvements in the software are of need to increase the efficiency of the demand response scheme.

Decarbonisation Relevance – Contribution to climate goals

The impacts on decarbonisation were limited in an absolute sense due to the pilot scale of the project and the size of the community. During the two years of operation, overall renewable electricity generation increased in the small system, and fossil fuel use consequently decreased.

Directly, the HSO scheme supplied 18 MWh of electricity demand (mitigated curtailment) by heat through the mitigated wind curtailment. Yet, indirectly, the electricity consumption grew by 68 MWh from 2018-2019 as 8 out of 72 properties in the scheme switched to electric heating from fossil-fuel based heating. Throughout the period of the project, it is reported that oil consumption (previously used for heating) dropped by 13,000 litres, solid fuel by 220 kg and liquid petroleum gas by 428 kg (Compton and Hull, 2022b). The project estimates that over the two-year pilot phase, 40 tonnes of CO_2 were avoided through a reduction in fossil fuel use. Yet only 20 % of the CO_2 reduction was directly caused by the scheme, the remaining reductions are due to the switch to electric heating in the 8 properties. The approach to calculate the emission reductions are shown in Table 4-2.

Scaling the emission reductions to other areas is difficult to assess, because it depends on the existing type of heating and how much renewable energy is available in the electricity system. We can however see that the HSO project supplied 1 % of the annual heat demand in the connected buildings using otherwise curtailed electricity. The switch from oil heating to electric heating likely has a higher impact in terms of reducing CO_2 emissions, but overall emission reductions in a year are subject to the carbon-intensity of the marginal unit supplying the electricity in the network. Flexible operation is necessary.

Table 4-2: Decarbonisation (annual calculation example, estimate)

Concept	Before the HSO project	After the HSO project
Number of properties	**72**	**72**
• Electric heating	19	27
• Fossil fuels (oil)	53	45
Annual heat demand per building	**20 MWh**	**20 MWh**
Total annual heat demand	**1,440 MWh**	**1,440 MWh**
• Heating devices	0 MWh	14 MWh
• Electricity (COP = 1)	380 MWh	535 MWh
• Oil (eff. = 80 %)	1,325 MWh	1,115 MWh
Total annual CO_2 emissions	**425 ton**	**410 ton**
Oil (74 kg CO_2 / GJ)	350 ton	300 ton
Electricity (200 g / kWh)	75 ton	110 ton

Security of Supply Relevance

The project was successful in reducing curtailment through activation of heating loads. curtailments of wind energy production could not be fully avoided though, due to limited heating demand, but also imprecise control signalling. The total marginal curtailment detected by the system during 2018 and 2019 was 98 MWh and 39 MWh respectively. The project's IT system needs to identify such curtailment measures first, before getting into action. Frictional losses are inevitable. The project was able mitigate 15 MWh (15%) and 3.3 MWh (8%) respectively. Much of the curtailments were detected by the system, but not mitigated due to limited demand from the heating devices (electricity demand for heating in the buildings had been satisfied).

Undetected curtailment also represented 18 MWh (18 %) and 19 MWh (49 %) of the total marginal curtailment in 2018 and 2019 from the wind turbine. Undetected curtailment can arise from communication errors between the controller installed on the heating devices and the main controller. By improving technology and software, the share of undetected curtailments can be reduced to below 5%.

The project reveals interesting insights on how a thermal system's electricity demand can be made flexible to help integrate VRE production. The underlying thermal infrastructure and the corresponding IT system are important for the ability to provide flexibility and help integrate VRE sources.

Lessons learned

There are several important lessons learned from the HSO project when it comes to the focus of this report in terms of security of supply and development of renewable energy. Most importantly, the HSO project was initiated because of the increasing wind curtailment levels experienced on the islands. These were due to grid congestions caused by increasing wind generation, while grid reinforcement could not keep pace to allow exports of excess VRE from the islands to mainland Scotland. The project serves as example on how to reduce curtailment measures, albeit – in the beginning – just one wind turbine as a test case. The HSO revealed the following lessons learned to be considered in similar projects:

- The regulation of the electricity market/system is important. On the Orkney islands, wind turbines were dispatched based on age – oldest wind turbines first. Thus, new turbines were operating with higher curtailment levels. In essence, using the otherwise curtailed electricity for heat production enables a higher operation of the wind turbines. In several balancing markets, wind turbines, electric boilers and heat pumps may end up competing on the same market for regulating services or may complement each other. Co-optimization is necessary. In the event of excessive generation (over frequency), the wind and demand will compete as resources to provide the downward regulation needed in the system and solve the system imbalance: wind decreasing generation (curtail) and electric heaters increasing demand. To avoid wind power curtailment, the electric boilers could utilize the wind energy, but the electric boilers could be competing at times with other assets in providing flexibility services in balancing markets. As such, VRE and electric heating can go hand in hand in reducing grid congestion and curtailments.
- It is difficult to predict the exact level of wind curtailment. Thus, there is a markedly visible amount of curtailment even after the implementation of the flexible heating devices. This is also due to the limited demand which in maximum could be activated through the heating systems and their storage capabilities. A well-functioning algorithm to detect and predict wind curtailment levels is key. Furthermore, offsetting the curtailment with increased electric heating demand had been easier if more houses had joined the project. With increasing shares of VRE, forecasting becomes a key element for the safe operation of VRE systems and to minimize curtailment events. Such tasks increasingly need to be carried out by TSOs.
- As the HSO project was not a greenfield project, it is based on individual heating devices with all its limitations. Central electric boilers connected to district heating and thermal storage however could boost the level of flexibility and put it to a larger scale. Especially, the use of thermal storage is key to enable flexible operation and reduce wind curtailment. Alternatively, the use of an individual combi-solution with a boiler together with electric heating can be a second-best option.

Looking Forward

The HSO project continues to operate and has since integrated more wind turbines into the scheme. Following the pilot phase, the project performed an analysis to estimate the breakeven point if the pilot were to be scaled up and connected to more generation assets. The project estimated that breakeven would be reached with roughly 5 wind turbines and 800 heating devices installed. HSO is seeking to increase its number of participants from 72 to 500 through 2024 and ultimately provide 50% of participating household's heating and hot water needs through HSO devices (Compton and Hull, 2022b). The HSO project continued its operation under "Project TraDER", which today has moved onto the "ReFLEX platform". The results of the project directly or indirectly spawned three other projects that seek to build upon the HSO project, incorporating more types of heating devices, offering multiple payment mechanisms, and addressing primary heating for all periods of curtailment.

Smart Islands Energy Systems (SMILE)

- SMILE[35] is supported by Horizon 2020 and considers nine smart grid solutions in three large-scale pilot projects in different regions of Europe with similar topographic characteristics but different policies.

[35] SMILE H2020 (h2020smile.eu).

- On Orkney, the aim of the SMILE project is to tackle current energy issues by combining a Demand Side Management system with the existing smart grid from the HSO project. This will allow for the intelligent control and grouping of electric heating systems in residential, commercial, and council buildings, as well as EV charging stations and electrolysers. SMILE builds upon HSO, which showed the feasibility of control technologies, communication systems, and commercial arrangements for integration with the smart grid.
- SMILE will expand the number of and types of assets able to participate in demand side management as well as explore a new implementation structure by operating as a new local energy company. The operating parameters and system specifications will be approved by the local DSO, which will also maintain final oversight of the system, but daily management will be handled by the local company and its contractors.

Responsive Flexibility (ReFLEX)

- ReFLEX Orkney aims to integrate not only heating devices as demand side management assets, but also electricity and transport assets via new software developments. To act as assets in an "integrated energy system", or Virtual Power Plant (VPP), the project will install the following:
    - Hydrogen Fuel Cell, for the provision of electricity and heat
    - Domestic energy storage
    - Commercial energy storage
    - Vehicle to grid charging infrastructure
    - Ground source heat pump systems
    - Building management systems
    - Integrated Grid-smart community-led transport system and infrastructure

Project TraDER

- Project TraDER (Transitional Distributed Energy Resource; ending in March 2021) sought to make it easier for new generators and demand assets to participate in a curtailment mitigation market. By allowing bid and offer prices to be set at the individual generator and device level, the overall value of the system from curtailment mitigation actions could be more accurately quantified, leading to improved benefits for device owners and better overall outcomes for the system. Specifically, the project sought to:
    - Quantifying the value to a generator from a specific curtailment mitigation action via a bid price
    - Quantifying the value that an end-customer/smart heating device gets from providing a specific curtailment mitigation action via an offer price
    - Creating direct matches or "trades" between individual device actions and generator need
    - Tracking proof of delivery from individual trades, which can in the future used for purposes of settlement and payments

4.4 Case Study 4: Virtual power plants (VPP) and provision of ancillary services

This case study was developed through literature review and interviews with an active aggregator operating VPP units in Italy, the Italian regulatory authority ARERA, and the Italian Transmission System Operator Terna.

Case Study: *Unità Virtuali Abilitate Miste* (UVAM) pilot project, Italy.

Main Hypothesis: there is a vast potential of flexibility capabilities from decentralised energy resources that are not used today for ancillary services, such as balancing markets. Setting the right market framework for aggregation can untap this potential and help decarbonise balancing services and enhance the overall flexibility in the system.

Description: the UVAM (*Unità Virtuali Abilitate Miste*, Virtually Aggregated Mixed Units) project was launched in November 2018 to pilot the participation of distributed energy resources (consumption, storage and generation units smaller than 10 MW) in ancillary service markets.

Key project basics:

- The UVAM pilot project has contributed to setting the rules for the participation of aggregated decentralized energy resources (DER) in ancillary services markets in Italy. Before the UVAM project, only conventional generators over 10 MW were allowed to provide these services.
- The UVAM pilot project has served as a demonstration phase of how DERs can effectively provide ancillary services. In practice, mostly upward balancing regulation (has been provided by UVAM units. Upward regulation refers to generators increasing production or demand reducing consumption from their scheduled dispatch.
- The UVAM project sits within the integrated regulatory framework for electricity dispatching Italy, which is now in the process of incorporating another project similar to UVAM for local ancillary services in distribution networks.

Key project results:

- The UVAM pilot project has successfully onboarded units previously not allowed to participate in ancillary services: 1,473 units[36] aggregated in 212 UVAMs, organised[36] by 31[36] balancing service providers (BSPs, operating as aggregators).
- The composition of UVAMs can be heterogeneous. Most UVAMs are composed by a single or two units (60 UVAMs and 79 UVAMs, respectively), while there were only a few UVAMs aggregating hundreds of units (4 UVAMs). Most UVAMs are concentrated in Northern Italy (90% of units), one of the 7 bidding zones of Italy. Units included in UVAMs are demand-side (mainly industrial loads, 48%), solar (33%), hydro power (8%), thermal (10%), renewable thermal (1%), and storage (0.1%)[36].
- UVAMs have provided mainly balancing services, especially upward regulation: 1,164 MW capacity upwards and 166 MW capacity downwards were, for example, contracted as of May 2022; 5.9 GWh of electricity balancing upwards and 0.8 GWh downwards were activated between April 2020 to June 2021[37].

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[36] Most recent available figures obtained from ARERA, the Italian National Regulatory Authority.

[37] Periods for data differ as they are defined according to the information available provided by the stakeholders interviewed or found in the literature.

- In general, there has been a low activation of UVAM resources, compared to their reserved capacity. The active participation of UVAMs in balancing services has been generally low (1.8% of the available balancing energy within the UVAM offers between July 2021 to March 2022[37]) due to high bid prices for energy activation (close to the price cap set by ARERA for UVAMs, now 200 and 400 EUR/MWh for *pomeridiano* and *serale 1* products[40]) that left them uncleared in the merit order of balancing bids. However, a positive trend is observed, comparing the 2020-2021 vs. 2021-2022 figures.
- Some UVAM units have been disabled for not passing reliability tests. Between August 2021 to April 2022[37], only 38% of 609 tests performed by the TSO had a positive outcome. All units whose tests were found negative 3 times were disabled from the UVAM program.

Key project takeaways:

- The main barrier for aggregators to participate in the project is economic, with underlying technical and market-regulatory requirements.
    - On the costs side, technical requirements include a high-resolution telemetry (4 seconds) involving important investments for aggregators to onboard and manage units to provide the contracted services.
    - On the revenue side, the current static price caps[38] (200, 400 EUR/MWh) can be lower than current day-ahead market price levels and potential penalties in the balancing markets (5,000 EUR/MWh) for called energy not activated. The current static price caps will be amended as dynamic price caps aligned to the market conditions. It must be noted that UVAMs who face this energy price cap are also remunerated for their balancing capacity contracted through a competitive auction. Non-UVAM balancing service providers do not receive any remuneration for reserved capacity, as it is the case in other European countries.
    - Also, the division of UVAM services into 2 block areas[39] and 3 products[40] was perceived by the aggregator interviewed as a market fragmentation issue for them.
    - The economic viability for participants relies on the balancing capacity remuneration, which is a payment for availability and subject to bids being offered, as balancing markets usually are pay-as-bid schemes). Revenues from energy activation represent a lower share due to high bid prices (presumably caused by the aggregation project economics) and a consequent low participation in balancing services.
- There are other multiple challenges for the large-scale participation of decentralized energy resources in ancillary services (some of which go beyond the scope of the UVAM pilot project). These concern:
    - **UVAM resources**
        - The expertise needed to make offers on balancing service markets.
        - The necessary technology to send data and manage activation orders according to the technical specifications of the TSO (ramping rates, minimum duration) with the time-resolution required. This can include

[38] The regulatory framework refers to this price cap as the strike price. The UVAM energy auctions have a pay-as-bid mechanism and the settlement price would be the price offered, which is limited to the strike price. To avoid confusion, we refer in the report to this strike price as the price cap.

[39] Area A (bidding zones Centro Nord and Nord) and Area B (Centro-Sud, Sud, Calabria, Sicilia and Sardegna).

[40] Pomeridiano: weekdays from 15:00 to 18:00; serale 1 and serale 2: weekdays from 18:00 to 22:00.

smart meters, data concentrators, router connection, connection to the asset, central control room, etc.

- **TSO/DSO resources**
  - The management and certification of metering data and subsequent economic settlement.
  - The capacity to know in real-time all available balancing resources and monitor their activation.
  - Potential issues of market liquidity in the development of local markets in the distribution system network.
  - The coordination between TSOs and DSOs to have access to flexibility resources and call their participation without generating issues to each other.
- **Regulatory issues**
  - Potential conflicts for UVAM members regarding the participation in balancing markets when renewable support schemes are in place. Such schemes can incentivise electricity production instead of participation in different markets, or even by regulation forbid participation in such markets.
  - The accurate design of the relationship between balancing service providers (BSPs) and balancing responsible parties (BRPs), their roles, responsibilities, operational and financial liabilities in the energy dispatch outcome from the provision of balancing services.
- **Technological challenges**
  - Technology standards needed for scalable solutions and the ease of the prequalification process.

Project description

In 2017, Italian Regulatory Authority ARERA (*Autorità di Regolazione per Energia Reti e Ambiente*) published the Resolution 300/2017/R/eel to initiate pilot projects for the opening of the transmission grid ancillary services to demand, VRE, and storages (ARERA, 2017). At the time, ancillary services were only open for conventional generation units above a nameplate of 10 MW. Italian TSO Terna developed successive pilot projects targeting different market agents:

- UVAC (*Unità Virtuali Abilitate di Consumo*, aggregated demand-side response) - June 2017 to November 2018
- UVAP (*Unità Virtuali Abilitate di Produzione*, aggregated generation, including VRE, and storage units connected at DSO level) - December 2017 to November 2018,
- UVAM (*Unità Virtuali Abilitate Miste*, Virtual Aggregated Mixed Unit, aggregated generation, demand, and storage) - from November 2018 until today.

A UVAM can include any combination of one or more small-scale renewable and non-renewable power plants, loads, larger production units not subject to mandatory ancillary service market participation, and energy storage systems. These can be connected to the grid at any voltage level, but must be within the same area to avoid the violation of network constraints (Gulotta et al., 2020). Italy currently has seven market zones[41]. A UVAM is thus a virtual power plant, a network of decentralized, medium-scale power generating units, flexible power consumers and storage systems (Next-Kraftwerke, 2022).

[41] For details, see e.g., https://lightbox.terna.it/en/

Thanks to the UVAM pilot project, UVAMs were allowed to provide services such as congestion management, balancing and secondary and tertiary reserves (TERNA, 2023a). Previously, ancillary services were restricted to conventional generation units larger than 10 MW. There are three products today served by UVAMs. *Pomeridiano*: weekdays from 15:00 to 18:00, *serale 1* and *serale 2*[42]: weekdays from 18:00 to 22:00. UVAMs can provide these services in two different assignment areas, which cover all seven market zones: Area A (market zones *Centro Nord* and *Nord*) and Area B (*Centro-Sud*, *Sud*, *Calabria*, *Sicilia* and *Sardegna*), who procure UVAM capacity separately with different quotas.

UVAMs are remunerated for both energy activation (EUR/MWh) and long-term capacity contracts for reserved capacity (EUR/MW/year). While the energy activation remuneration is the result of UVAMs being cleared in the Italian balancing energy market (*Mercato Servici Dispaciamento – MSD)*, as any other BSP unit, the capacity remuneration is exclusive for contracted UVAMs, and it is not paid to other non-UVAM BSPs. Nevertheless, contracted UVAMs are capped for their energy activation bids, while this is not the case for the other BSPs. The price cap for UVAM offers is today 200 EUR/MWh (*pomeridiano* and *serale 2*) and 400 EUR/MWh (*serale 1*). For the long-term capacity contracts (exclusive for UVAMs), started in January 2019, the TSO procures a certain quota of capacity (i.e., 1 GW in 2019 and 2020) in forward contracts, allocated through auctions on a fixed premium, with price caps of 22,500 EUR/MW/year (*pomeridiano*) and 30,000 EUR/MW/year (*serale 1* and *2*), and a pay-as-bid mechanism.

The capacity remuneration is paid upon a commitment to submit offers for the whole contracted capacity for balancing service during the product time frames for at least two consecutive hours. If the minimum offer obligations are not respected for at least 70% of delivery days, the capacity remuneration is cancelled. Balancing capacity auctions take place on a yearly, intra-annual, and monthly basis, up to the saturation of the capacity made available by the TSO for each area. As indicated in (Gulotta et al., 2020) and confirmed by Terna and ARERA in the interviews, the capacity remuneration of UVAMs was introduced for the project pilot demonstration phase. It is aimed to help aggregators cover investment and operational costs of all equipment they need to install to onboard units in their pools. However, after the pilot phase, all units have to operate purely competitively. As of today, there is no capacity remuneration in the Italian balancing services, but this can change in the future as commented by the Italian regulator.

The UVAM pilot project represents the first integration in Italy of decentralised energy resources for the provision of ancillary services to the power grid (balancing services and congestion management) (Gulotta et al., 2020).

Overall objectives

The objective of the UVAM pilot project is to test the ability of aggregated decentralised energy resources to provide ancillary services in Italy. The final goal of ancillary services is to ensure the grid stability.

From the TSO's perspective, the UVAM pilot project is used as a testing phase for decentralised energy resources to demonstrate that they can deliver ancillary services within the defined technical specifications.

[42] Differentiated by the price cap level.

From the NRA's perspective, the UVAM pilot project objective was to enable a technology-neutral market framework removing all unnecessary entry barriers for decentralised energy resources in ancillary services. In this regard, the minimum capacity requirement (10 MW) for single units was removed, the aggregation concept was allowed, new unit types (renewables, demand, storage) and their combination were allowed, the possibility to qualify for one single service, and the asymmetry of upward and downward regulation services was also introduced.

State of the art in Europe

The opening of balancing services to non-conventional generation resources (other than dispatchable thermal or hydroelectric powerplants) has also been facilitated in other European countries. According to the most recent survey on ancillary services and cross-border balancing initiatives by ENTSO-E, 6 of the 30 European countries who answered the survey (EE, GR, LV, RO, RS, and MK) restrict ancillary services to generation only (ENTSO-E, 2022e). According to (DNV, 2022), almost all[43] European countries included in the analysis[44] allow the aggregation of resources and the participation of demand-side response for the provision of some or all balancing services. Note that the situation can vary by product (frequency containment reserves - FCR, automatic frequency restoration reserves - aFRR, manual frequency restoration reserves – mFRR, replacement reserves - RR, and other non-frequency regulation services). Although allowed in other countries, the actual participation of aggregated DERs in ancillary services in Europe is, in general, limited. The UVAM pilot project is a regulatory framework to foster this participation at a pilot stage.

Project monitoring

The participation of UVAM resources in the market and their operation in the provision of ancillary services is closely monitored by the TSO. Terna reported the UVAM pilot project as very valuable in assessing how new resources such as batteries and industrial loads can provide ancillary services. In a future system with vast variable renewable penetration levels and a lower installed capacity from synchronous conventional generators[45], there will be an even higher need for ancillary services. It will be important to ensure that all flexible resources will be enabled to participate in the ancillary services markets.

In the longer run, decentralised energy resources will participate in ancillary services to a larger extent, mostly through aggregation. (DNV, 2022) estimates a potential of 164 GW and 130 GW of upward and downward flexibility from demand-side-flexibility resources in Europe. The UVAM pilot project can be a kick-start for untapping flexibility from decentralised energy resources.

[43] Only Poland, Latvia, Romania, Greece, and Portugal were evaluated to not effectively allowing aggregation or demand flexibility access to balancing services, although expected national regulatory developments may change this situation in the coming years.

[44] Austria, Belgium, Denmark, Estonia, Finland, France, Germany, Great Britain, Greece, Hungary, Ireland, Italy, Latvia, Netherlands, Poland, Portugal, Romania, Slovenia, Spain. Sweden, Switzerland.

[45] Synchronous power-generating modules are installations which can generate electrical energy such that the frequency of the generated voltage, the generator speed and the frequency of network voltage are in a constant ratio and thus in synchronism. These are traditionally conventional thermal plants. Wind and solar generation, in contrast, is non-synchronous.

Resources allocation

Organisational resources were dedicated from both ARERA and Terna to develop the UVAM project, first in the development of the regulatory market framework and specific guidelines, and then in the operation of the project. Below we describe a list of specific processes that involved resources from the project developers.

In the development of the regulatory framework:

- General regulatory framework (*Resolution 300/2017/R/eel)* by ARERA, which defines the principles and general criteria for the pilot project UVAM (ARERA, 2017).
- Specific technical rules (TERNA, 2017) defined by Terna and approved by ARERA.
- Coordination between the ARERA and Terna, accompanied by public consultations.

In the operation of the project:

- Prequalification of UVAM units by Terna.
- Reliability and availability tests performed by Terna on approved UVAM units.
- Tendering of balancing capacity reserves from UVAM resources (there are annual and monthly tenders) by Terna.
- All processes related to the actual operation of UVAM resources in the ancillary service markets: clearing of balancing energy auctions (*Mercato Servizi Dispaciamento* and *Mercato Bilanciamento*), calls for activation of resources, monitoring of service provisions, and economic settlement of services provided. These are also managed by Terna.

Synergies with other initiatives or projects

Terna mentioned that the UVAM pilot project can be considered a stand-alone project, but it has synergies with other projects, like those listed below. Note that except for Equigy, where UVAMs can use the platform, the other two projects do not have a direct relation to UVAMs, the synergy being about the similar topic addressed, namely flexibility from DERs.

- the Equigy project (Equigy, 2022a)[46]: a flexibility platform developed by several European TSOs that aims to facilitate the provision of ancillary services by aggregated decentralised energy resources. UVAM resources can now prequalify assets via Equigy.
- The EU-funded "Flow project" (Flexible energy systems Leveraging the Optimal integration of EVs deployment Wave)[47]: Horizon Europe project promoting a suitable electric mobility concept for end users while optimising electric vehicle grid integration, with five demonstration sites to be set up in CZ, IE, IT, ES (Electrive, 2022).
- BEFLEXIBLE[48]: the project aims to increase the flexibility of the energy system, improve cooperation between TSOs and DSOs and facilitate the participation of all energy-related stakeholders (BeFlexible, 2022). The project takes place in several shapes in Italy, Sweden, Spain and France.

ARERA released in August 2021 a new regulatory framework to develop pilot projects about local ancillary services[49] in distribution networks, *Delibera 352/2021/R/eel* (ARERA, 2021). The

[46] https://equigy.com/

[47] https://www.theflowproject.eu/

[48] https://beflexible.eu/

[49] Focused on congestion management of distribution networks, which can be especially relevant in grids with high growths of new electric load types (EV charging and heat pumps) if the grid is not adequately reinforced.

regulation can be considered a continuation of the regulatory framework for UVAM at DSO level, instead of national TSO level. As of today, the design, detailed rules and requirements of these local markets are under development by the different DSOs in Italy, notably Enel Distribuzione (E-distribuzione, 2022), who operates around 80% of the distribution networks in Italy. As with the UVAM specific rules designed by Terna, there will be a public consultation phase and a final approval from ARERA. These rules are expected to be defined in 2023. All regulations will be included in the integrated regulatory framework for electricity dispatching (TIDE - *Testo integrato del dispacciamento elettrico*), to be issued in 2023 and expected to be in force from 2025, as presented by ARERA in the interview.

Policy cohesion/adherence

The regulatory framework 300/2017/R/eel that initiated the UVAM pilot project involves an alignment with the Electricity Balancing Guidelines (EC, 2017). According to these guidelines, balancing service rules should "ensure adequate competition based on a level-playing field between market participants, including demand response aggregators and assets located at the distribution level" (EC, 2017).

The UVAM pilot project is also commented in the Italian Integrated National Energy and Climate Plan (NECP) in the context of the national objectives with regard to increasing the flexibility of the national energy system, in particular by means of developing domestic energy sources, demand response and storage (Ministry of Economic Development et al., 2019).

The UVAM pilot project and the opening of ancillary services to demand response and aggregation has also to be considered in the light of the new European framework guidelines on demand response, which are today under development by ACER (ACER, 2022e).

Technical-regulatory challenges

As discussed in the interview with ARERA, technical challenges for a decentralised energy resources to participate in balancing services can include the technologic requirements to send data and receive dispatching orders according to the technical specifications of the TSO (ramping rates, minimum duration). Another technical challenge for the system operators (TSOs, DSOs) is to know in real-time all available balancing resources and monitor their activation.

In this same line, metering and communication infrastructure requirements were found to be a barrier by an aggregator interviewed for this case study. The current telemetry required by Terna has a minimum resolution of 4 seconds. This entails a considerable investment for the aggregator in metering and communication infrastructure to onboard and operate new balancing service units. Investments can include smart meters, data concentrators, router connection, connection to the asset, central control room, etc. Note that not all investments are strictly linked to the 4-second telemetry requirement, but to the overall requirements of the process to provide ancillary services by aggregating distributed resources. In the interview with Terna, it was stated that a high-resolution telemetry is needed to monitor the adequate provision of the services. It must be kept in mind that this high-resolution telemetry requirement is also required in most European countries.

(Smart Energy Europe, 2022) also concludes that real-time transmission of data is a main barrier for the development of demand side flexibility in ancillary services that can quickly overburden the IT systems of aggregated groups. This report mentions the example of experimental frameworks in France, where smaller units are allowed to provide an estimate of generation or consumption instead of real-time telemetry data and provide high-granularity data for ex-post verification when required. This could greatly reduce costs for the aggregators while not impacting the ability of TSOs to monitor the performance in the provision of the services. This comparison should be taken with care and is brought as an example of alternative practices in another EU country. A further analysis would be needed to assess whether the cost savings for the aggregator compensate the potential issues derived from estimated real-time metering data, like the decrease in the performance of the provision of the services or problems in the final settlement.

ARERA also mentioned a need for technology standards to make scalable solutions and simplify among other processes, the prequalification process. The standardization of technologies around original equipment manufacturing of decentralized energy resources (heat pumps, EV charging stations, etc.) and associated communication infrastructure can be an initial challenge but mean a large opportunity to reduce costs of provision of balancing services, under a scheme of ready-purposed devices to "plug-and-play" in the provision of services to the grid by aggregators. The Equigy project, a flexibility platform developed by several European TSOs aimed at facilitating the provision of balancing services from decentralized energy resources (see above, under 'Synergies with other initiatives or projects'), points at the importance of standardization to integrate smaller devices to balancing markets (Equigy, 2022b). In the interview with Terna, standardisation of processes, and the design of standard platforms to access ancillary services, like the Equigy platform, were found to be useful in lowering the costs for DERs to participate in ancillary services markets.

Market-regulatory challenges

ARERA pointed out that providing balancing services requires some expertise. This expertise can be well developed by aggregators during the UVAM pilot phase.

In the development of local flexibility markets for distribution networks, there can be potential issues of market liquidity[50] that need to be avoided (for example, by removing all potential barriers for the participation of DERs in these local flexibility markets). The less the market liquidity, whatever market it is, the higher probability of market abuse and excessive prices. Note that local flexibility markets are out of the scope of the UVAM pilot project but are however highlighted since the expected growth of decentralised energy resources connected at low and medium voltage will very likely make these local grid services necessary in the future. Flexibility at the DSO level can solve several critical issues in the distribution network (notably congestion management) and possibly help reduce infrastructure investments.

Another regulatory barrier found by the aggregator interviewed was the potential market fragmentation derived from the structuring of UVAM products into two geographic areas (A and B, covering all seven market zones in Italy) and 3 different products (*pomeridiano* and *serale 1* and *2*). They also found that both balancing capacity and balancing energy remuneration price caps can be too low to have a business case as an aggregator. For the former, currently set to 22,500 EUR/MW/year for the *pomeridiano* product and 30,000 EUR/MW/year for the products *serale 1* and *2*, the aggregator suggested a higher alternative cost referenced on the annualized investment cost of building a peak-gas power plant, i.e., 75,000 EUR/MW/year. On the energy remuneration price cap (*pomeridiano* and *serale 2*: 200 EUR/MWh, *serale 1*: 400 EUR/MWh), it was commented that these prices caps are static and can be lower than the current wholesale

[50] Liquidity problems can also arise in the TSO national flexibility market, but they can be more acute the smaller the market area is.

prices, which result in losses for an industrial load who has purchased electricity at the spot price and then provides upward regulation (cease consumption), which will be reimbursed at a lower price. Regarding the static energy offer price caps, ARERA pointed that the recent Resolution 702/2022 (ARERA, 2022b) requires TERNA to issue new rules for the UVAM project which include variable price caps according to market conditions.

Last, it was mentioned that the potential penalties incurred for not providing a balancing service can reach 5,000 EUR/MWh (general price cap in the *Mercato Bilanciamento*), which are not aligned with the bid price caps they can offer (200 and 400 EUR/MWh).

From all interviews maintained for this case study with the Italian NRA, TSO and an aggregator, the major barrier for UVAM participation seems to be economic. The low activation of UVAM resources due to energy offers close or equal to the price cap, in general above the balancing service prices offered by non-UVAM resources, point at a competitiveness problem today compared to conventional resources. The economic barrier can be worsened if the balancing capacity remuneration is removed for UVAM resources when the UVAM pilot project is ended. This is not certain today and the future regulatory framework may also incorporate balancing capacity payments for all BSPs (as it is done in other European countries). In a context where up-front costs become relevant compared to costs of operation, an energy-only remuneration may not be sufficient to provide the adequate forward price signals to stimulate new investments, at least when looking at balancing market opportunities only.

In the European context, (Smart Energy Europe, 2022) identifies different regulatory barriers in ancillary services; among them, the symmetry of balancing products (equal obligation to provide upward and balancing regulation) present in some European countries. This was however removed in Italy under the UVAM market regulation.

The availability and accuracy of response requirements is also considered a barrier in (Smart Energy Europe, 2022) where it is suggested that penalties or quarantine periods are applied to units not complying with availability or service provisions, in order to avoid disqualification of units as it is the case in Italy, in case when 3 reliability tests are not passed within a year. (Smart Energy Europe, 2022) also reflects that availability and service provision should always be tested for the aggregated balancing service group and not for specific units.

Other regulatory barriers mentioned in (Smart Energy Europe, 2022) point at a too high minimum bid sizes in some European countries that can prevent the participation of small aggregators focused on low voltage small devices like charging stations or household solar PV. This was not however mentioned as a barrier by the aggregator interviewed, although acknowledged it could be a barrier for other aggregators. In Italy, the minimum bid size for balancing products is 1 MW[51].

Last, the prequalification process is also listed in (Smart Energy Europe, 2022) as a potential barrier. It is mentioned that in many European countries, the prequalification process must be repeated by a balancing service group of assets for any modification, even if minor, in its composition. According to the Italian TSO, new prequalification tests for UVAMs are only required when the composition of their units changes the UVAM capacity by more than 30% or when changes involve a variation in the UVAM's composition (demand/storage/VRE unit types).

[51] Please note this is not the same as the 10 MW minimum size for BSPs in place before the UVAM pilot project.

Technology standardisation could help in this regard to automatically prequalify asset types that have already been prequalified within a balancing service group (like in the Netherlands). The aggregator interviewed did not point specifically at the prequalification process as a major barrier to their business, but they would encourage a homogenisation in Europe of all processes around balancing service provision, including prequalification, technical requirements, minimum bid size, etc., and avoid to the extent possible different implementations of balancing markets per country. Note that a full homogenisation of ancillary service processes in Europe can be unrealistic or impractical to address specific country needs.

(Smart Energy Europe, 2022) also concludes that in some countries the participation of aggregated units and demand-side flexibility, although theoretically possible, is almost inexistent due to practical market-regulatory barriers (e.g., high minimum bid size, undeveloped prequalification procedures, undefinition of the aggregator role in the national legislation or inexistence of these in the country, etc. In all countries analysed, some degree of the previous barriers was identified for the participation of aggregated units and demand response. Regarding barriers related to the prequalification process, the study in (ACER, 2022d) showcases some practices that could be considered by TSOs to improve and simplify the product prequalification process for new and small market participants, including demand response:

- Setting a product prequalification for groups aggregating any type of technology
- Setting a threshold for re-prequalification only after significant changes in prequalified units or groups
- Using type-approval for small units
- Verifying the compliance of assets to technical requirements during the service delivery rather than before.

Cooperation/Coordination Challenges

There can be potential conflicts in the provision of balancing services with renewable support schemes that incentivises the maximisation of generation (e.g., feed-in-tariff). A fixed payment price for every MWh generated can conflict with the provision of a downregulation service.

There can also be challenges in the coordination between TSOs and DSOs to have access and call flexibility resources without generating issues towards each other. It can happen that a TSO calls some decentralised energy resources connected to the distribution grid for a national grid service but generate a local congestion issue in the network where these resources are connected. With the deployment of decentralised energy resources, these situations are likely to happen more often, why a better coordination is needed between TSOs and DSOs than today. This challenge is mentioned in numerous reports, including (Gerard et al., 2016) and (ENTSO-E, 2019b). There is currently an ongoing consultation in Italy for a specific pilot project for the TSO-DSO cooperation, where UVAMs will be involved (TERNA, 2023b).

Last, the accurate design of the relationship between balancing service providers (BSPs) and balancing responsible parties (BRPs) can also be a challenge for the participation of decentralised energy resources in ancillary services. BSPs' and BRPs' roles, responsibilities, operational and financial liabilities in the energy dispatch outcome from the provision of balancing services must be clear and prevent that BRPs may incur losses for BSPs activations of assets belonging to the BRPs' portfolios. BRPs, on their side, must be liable to fulfil the scheduled program of all assets in their portfolio.

Decarbonisation Relevance – Contribution to climate goals

The UVAM pilot project is highly relevant for decarbonisation. Ancillary services are predominantly serviced by conventional thermal generation in Europe (and hydroelectric power plants where available). For example, (Lafratta et al., 2021) estimates that only 8% of balancing services in Great Britain come from low-carbon generation. Therefore, all market capture from the decentralised energy resources targeted by the UVAM pilot project, which include demand response or renewable generation, can signify a reduction in emissions from these services. ENTSO-E's 2021 Market Report statistics show around 20 TWh of electricity generated for upward regulation in Europe in 2020 (ENTSO-E, 2021a). Assuming the emission factor of a gas-fired peak power plant at 488 kg CO_2/MWh, the potential CO2 savings could be 9 million tons of CO_2 per year if all upward regulation would have been provided by demand response or renewable assets[52].

Security of Supply[53] Relevance

The UVAM pilot project is of high relevance for security of supply as well. The project is focused on ancillary services, and mostly implemented on balancing services in Italy, whose purpose is to ensure the stable operation in the grid by maintaining the European-wide 50-Hertz frequency, which relies on the supply-demand balance in the system.

In a future power system dominated by variable renewables, there will be a higher need for ancillary services. It is essential that all flexible resources connected to the grid (with expected high installed capacities of decentralised energy resources) can participate in ancillary services. The UVAM is seen by the Italian NRA and the TSO as a testing environment for the participation of decentralised energy resources in ancillary services.

Lessons Learned

The UVAM project has facilitated the participation of 1,473 decentralised energy resources in the Italian ancillary services market. It has helped test their ability and reliability to provide these services and lays the groundwork for their wide-scale participation in the future. This will become increasingly important with the growing balancing service needs in a system with more and more fluctuating VRE generation and a lower share of synchronous capacity.

There are today numerous challenges for the wide-scale provision of balancing services (and flexibility services in a more generic concept) by decentralised energy resources. The main barrier today for aggregators to participate in balancing services seems to be economic or a lack of competitiveness with conventional resources, as it was pointed by the Italian TSO and ARERA, and as it is evidenced by the low participation of UVAMs due to high bid prices in the balancing energy market auctions (MSD).

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[52] Please note this is a theoretical gross estimation to have a reference magnitude of potential carbon savings and not a precise estimation of the decarbonisation potential from the provision of balancing services by decentralised energy resources.

[53] It must be stated that UVAM services are limited to ancillary services, needed for the safe operation of the grid (under the adequate frequency and voltage levels). Ancillary services do not address system adequacy, which has a longer-term perspective as opposed to ancillary services, which concern the operation of the system in real time. Security of supply relevance must be understood in this case the as security in the operation brought by ancillary services.

On the cost side, expenses may be mainly driven by the investments in metering and communication infrastructure needed to fulfil the high-resolution telemetry and the overall technical process of the service provision, as required by the Italian TSO. The high telemetry is nonetheless found necessary by the TSO to be able to monitor the adequate provision of the services.

On the revenue side, current static price caps to energy offers from contracted UVAMs (who are also remunerated based on their reserved capacity) are of concern to the aggregators since they can misalign with wholesale prices and case potential losses for providing balancing services. Yet, these static price caps will be changed to dynamic price caps aligned with the market situation. Regarding balancing capacity payments, these seem to be strongly needed to sustain the aggregators business as of today. To make UVAMs compete at a level-playing field with non-UVAM resources, extending the remuneration of balancing reserved capacity for non-UVAM resources instead of removing the remuneration to UVAMs can be seen as a more favourable option to incentivises the participation of decentralised energy resources, which at some point will be strictly needed with the progressive closure of conventional fossil-fuelled resources. Balancing capacity remuneration is available in many European countries for all BSPs.

Outside of the scope of the UVAM pilot project, there is a high value in the availability from decentralised energy resources in the system that goes beyond the value of their actual activation, which may call for a remuneration for capacity made available. Forward markets, needed to reserve capacity or long-term contracts, reward investments in capacity. It could be argued however that complementary market instruments can help, in addition to energy-only markets (see chapter 2.3 Solutions, esp. Capacity mechanisms, CfDs, PPAs). Capacity remuneration mechanisms (addressing system adequacy problems and beyond the scope of the UVAM framework which is strictly related to capacity reserved for ancillary services) were mentioned to be a clear opportunity for demand response services to the system by the aggregator interviewed.

Looking Forward

There is not a date to end the UVAM pilot project, which has been in a pilot phase since 2018. The expected way forward is nonetheless the integration of UVAM resources in ancillary services as any other market player. The UVAM regulation was part of a broader regulatory framework revision, the integrated regulatory framework for electricity dispatching, TIDE - *Testo integrato del dispacciamento elettrico*, currently under consultation (ARERA, 2022a). A successive regulation similar to the UVAM but focused on local ancillary services in distribution networks was released by the Italian National Regulatory Authority, *Delibera 352/2021/R/eel* (ARERA, 2021). The specific rules and design for the provision of these local ancillary services are under development and consultation by distribution system operators. These are planned for 2023 (ARETI, 2023) (E-distribuzione, 2023). A pilot project for the TSO-DSO coordination is also under consultation (TERNA, 2023b). As presented in the interview with ARERA, TIDE is planned to be issued in 2023 and expected to be in force from 2025 onwards. This final regulation will include an overarching regulatory framework in Italy for TSO and DSO local grid services, open to all unit types, including decentralised energy resources with small generation (renewable and non-renewable), and demand response.

5 Policy toolboxes and recommendations

Decarbonisation and security of energy supply are two main areas under strain today in the European energy system. As it works to respond to these challenges and to the unforeseen global disruptions affecting energy supply, the EU energy policy landscape is evolving. Since 2021, we have seen a reopening of the economy post COVID-19 driving up electricity demand, the Russian invasion of Ukraine and subsequent throttling of the natural gas supply from Russia resulting in record high natural gas prices and gas and electricity savings in 2022. Across some Member States, conventional thermal power plants were re-fired to help make up for lost gas resources and for exceptionally low nuclear and hydropower output in 2022. Together, this led to an upward spike of the otherwise decreasing GHG emissions trends in the EU, with 2021 recording an increase in emissions of 6% (reopening of the economy and gas to coal switch in the second and third quarters of 2021, as gas prices skyrocketed and more conventional thermal generation was leveraged to maintain security of supply) **(EEA, 2022d)**.

To avoid such negative impacts also in the future, the EU has in its policy developments accelerated the green energy transition. Building on the 750-billion-euro Next Generation EU package agreed in 2020, EU furthered its ambition on climate and energy targets in 2022 with the RePowerEU, and provisional EED and RED agreements, intending to increase energy efficiency and renewable energy production targets across the EU, while encouraging overall energy consumption reduction. The benefits from the stimulus have yet to pay climate dividends and there remains a significant amount of money to be spent on energy and climate initiatives. This is especially important as Member States are currently revising their resource and recovery plans, of which 37% of initiatives are to be earmarked for energy and climate initiatives and must submit by June 2023 draft updated national energy and climate plans for 2030 that reflect higher level of ambition.

From the research, interviews and case studies examined in this report, there are a variety of existing solutions that may be implemented to continue the trend of decarbonisation without compromising security of supply. It is the intent of this chapter to show which policies and measures deserve more attention to progress the energy transition in the EU.

The challenge of upholding a high security of supply in a decarbonised electricity system is to some extent an issue of matching VRE generation and demand (including sector coupling with transport, heating/cooling, and hydrogen). To do this, flexibility resources will be key. Thus, key policy recommendations are presented below, grouped into four categories, without any specific ranking of importance or salience: infrastructure-side flexibility, supply-side flexibility, demand-side flexibility, and storage flexibility.

5.1 Infrastructure-side flexibility

The EU has been working to create an integrated and interconnected electricity market, with a focus on improving security of supply and flexibility through cross-border cooperation and interconnectors. To this end, the EU has established several policy initiatives and specific funding programs to promote the development of interconnectors and cross-border cooperation in the energy sector. The revised TEN-E regulation (EC, 2022l) creates a regulatory framework for cross-border Projects of Common Interest (PCI) which can benefit from reduced permitting complexity and have access to EU funding. To support the rapid increase of renewable energy and help transforming the energy system, the EC has recently recommended a set of measures, including on speeding up permitting provisions for renewable energy projects(EC, 2022i). An overview of relevant policies and measures for the electricity grid infrastructure to adapt to changes in the demand and supply of electricity, also referred to in this report as infrastructure-side flexibility, can be found in Annex 1.

The following list of measures can be relevant to improve infrastructure-side flexibility:

- **Building efficient physical infrastructure for offshore energy systems**. Europe has high targets to develop offshore wind and other marine renewable energy in Europe, with at least 60 GW of offshore wind by 2030 and 300 GW by 2050 (EC, 2020d). Developing this potential requires a more complex interconnection infrastructure than the traditional radially connected offshore wind farms to shore. Offshore energy hubs, energy islands, and hybrid interconnectors are the infrastructure concepts under discussion today. There is consensus that these hybrid systems combining offshore generation and cross-border interconnectors bring welfare gains by allowing an increase in market integration, a more efficient sharing of renewable resources between countries, a more coordinated investment planning, a decrease in system costs (by the sharing of common infrastructure), a lower need for additional connection points, and a more limited impact on the environment than radial connections to shore.
- **Developing efficient market and regulatory frameworks for offshore energy systems**. The adequate market and regulatory framework for offshore energy systems should be defined to incentivise the deployment of offshore renewable energy, while considering the system-wide impacts of these investments. There is consensus today that the most efficient market outcome is achieved under offshore bidding zone arrangements, but discussions continue as there are not yet any examples of offshore bidding zones in operation. The only existing offshore hybrid interconnection project today is the KFCGS, which has a home market bidding zone structure (the Kriegers Flak wind farm belongs to the Eastern Denmark bidding zone and the Baltic 2 wind farm belongs to Germany[54]) and its interconnector was granted an exemption to the 70% interconnection availability requirement for cross-border trade to avoid any potential negative effect on the economics of the offshore wind farms. Although the derogation of the 70% rule benefitted the implementation of the KFCGS project, derogations are not to be preferred as a solution for future projects (ACER and CEER, 2022). A wider regulatory framework that considers the particularities of offshore hybrid systems should be

[54] To help identify constraints in the transmission grid, Germany has four bidding zones; however, all four are operated at the same price(NordPool, 2023).

defined to ensure an enduring regulatory solution. Offshore bidding zone market arrangements can prevent the need for the 70% derogation in hybrid interconnection systems in future projects.

- **Using locational price signals.** Locational pricing signals (energy prices and tariffs) can be important in driving efficient investment decisions in the energy market. Locational market price signals incentivize interconnection investments, generation, and demand assets where these are needed most. Generation is incentivized where prices are higher, demand where prices are lower and interconnectors where there are higher cross-border price differentials. Today, across the EU market price signals are defined based on a zonal electricity market, in which prices are being geographically defined by the configuration of bidding zones. When developing bidding zones, it is important to balance large zones to ensure liquidity and prevent market power, while also ensuring that market zones are aligned with the physical limitations of the grid. This requires considering several factors (transmission capacity, geographic features, load patterns, etc.). Ultimately, the goal is to create a market structure that promotes competition and efficiency, while ensuring grid reliability and stability.

- **Designing efficient local energy systems that maximise the use of the available energy**. As of today, plenty of excess energy (curtailment) and VRE is available but not utilized as the necessary integrated energy infrastructure is not available and the right incentives are not in place. Encouraging energy efficiency measures and smart solutions focusing on economies of scale are required. This also puts an emphasis on selecting the right technologies for the right place, while keeping the local energy system in mind. Over-developing VRE sources that cannot be utilized due to grid constraints raises the need for co-optimising the planning of the relevant energy vectors. Encouraging viable business cases for the development of energy communities that contribute to overall system efficiency is important**(EEA, 2022c, 2022a)**. Financial support may be needed at the onset of such projects.

5.2 Supply-side flexibility

The EU's strategy on energy system integration, adopted in 2020, aims to further enhance the flexibility of the electricity system by, among others, promoting the integration of renewable energy and the development of cross-sectoral energy system integration. An overview of relevant policies and measures for the supply-side flexibility can be found in Annex 1.

The following list of measures can be relevant to improve supply-side flexibility:

- **Encouraging the development of hybrid energy projects.** The Haringvliet (HHEP) case study is an example of how supply-side flexibility can be enhanced through the development of hybrid energy parks, in this case complementary wind and solar generation combined with a battery electric storage system. The combination of wind turbines and solar panels allows for a more stable energy supply as they can produce electricity at different times of the day and year. Additionally, by storing energy during times of excess supply, a battery system in a hybrid energy park can help reduce the need for peak power plants to supply electricity during peak periods of demand, by this helping to decarbonize the energy system and increase security of supply. The potential for cable pooling can lower the investment costs and the complementary production profiles of wind and solar generation can bring further advantages. To facilitate the development of hybrid parks, zoning and land use policies must be created. Additionally, policies specifically tailored to the needs of hybrid energy parks, as well as subsidies can encourage the development of hybrid projects.

- **Smart sector coupling.** The Heat Smart Orkney (HSO) case study demonstrates that technologies can be brought together to intelligently control electrical demand for heat production to reduce or prevent wind turbine curtailment. The integration of VRE sources can be improved by developing intelligent sector coupling measures. The sector coupling flexibility is not only related to the electricity market regulations but equally to the development of the energy infrastructure. As the transport and the heating and cooling sectors undergo electrification, they are becoming key enablers for the integration of VRE sources. Nevertheless, an uncoordinated use of individual heating devices instead of, for example, coordinated ones and central district heating and cooling systems, can limit the level of flexibility provided by the electrification of heating needs in buildings. By contrast, the use of thermal storage in buildings can unlock flexibility of the heat demand and reduce thereby VRE curtailment. While residential hydrogen-based heating appears to be an inefficient and expensive way to use limited hydrogen resources (EEL, 2022; BEUC, 2022), the development of a future renewables-based hydrogen system with hydrogen storage options can become highly relevant for the overall security of the energy system (see also Section 5.4, Storage flexibility, below).
- **Promoting the advancement of flexible sector coupling technologies by regulatory changes.** It is essential to make several regulatory changes, for example to establish support schemes and adjust taxes and tariffs to be variable in time, to ensure advancement of the necessary sector coupling (flexibility) technologies at both local and national levels. The Heat Smart Orkney project has highlighted the importance of involving the local community and ensuring economic value sharing. The community-based approach to developing shared flexibility schemes for the heating sector are an example of how to maximize the efficiency and value creation by new forms of public-private cooperation. Future regulatory changes should incentive development of flexible technologies and provide the right signals for flexible operation, which can be leveraged by digital solutions coupled with flexible technologies, increasing system efficiency, and maximizing utilization of variable renewable energy.
- **Exploiting VRE complementarity in energy planning.** Combining diverse renewable technologies and sharing renewable resources across geographies brings complementarity effects, evidenced in this report in lower variability, a better correlation to demand, and a higher minimum available generation. These complementarity potentials should not be disregarded when developing energy system planning exercises at European or country level to find the most efficient pathways towards a secure and decarbonized European electricity system.

5.3 Demand-side flexibility

Demand response solutions may have been overlooked in the past by policymakers when considering energy and climate policy goals. Yet today, there are ongoing regulatory developments focusing on demand response, such as the framework guidelines on demand response **(ACER, 2022g)**, or The recent Electricity Market Design proposal **(EC, 2023b)**, which includes market measures to strengthen demand response. Overall, previous EU energy and climate targets have aimed at integrating more renewable sources and improving energy efficiency (energy consumption reduction) in the energy system to displace conventional thermal generation assets, rather than focusing on the demand-side, with measures and policies to foster demand response flexibility. An overview of relevant policies and measures for the demand-side can be found in Annex 1 – EU policies and measures.

Although according to the Regulation 2019/943 on the internal market for electricity **(EC, 2019f)**, demand response should be able to participate in all energy markets on a non-discriminatory basis, the actual participation of demand response in energy markets is very limited to date and specific regulatory developments are still needed to tackle issues around the effective participation of demand response and demand aggregation business in electricity markets.

Issues around demand response participation can include the economic settlement of deviations considering the net position and the provision of balancing services, which can result in imbalance payments or penalties for not providing agreed services, the coordination between balancing service providers and balancing responsible parties when demand response is activated, prequalification processes for demand response and balancing service groups, data exchange between system operators about demand side flexibility in the planning, operation and settlements of system services, or how demand response can be used for congestion management and voltage control services.

Currently, the framework guidelines on demand response are being revised **(ACER, 2022i)**, a draft new version having recently been released by ACER for public consultation. This new draft version addresses some of these specific matters on demand response and aggregation.

The following list of measures can be relevant to improve demand-side flexibility:

- **Enabling the participation of small, decentralized assets.** Smaller decentralized assets, especially those less than 1 MW, such as buildings, smaller industries, and retail customers, have historically not been allowed to actively participate in electricity markets. Yet, the benefits of demand response, when aggregated, allow customers of any kind to respond to signals from a grid operator and ramp up or down their consumption in a way that benefits the operation of the grid. The potential benefits resulting from the scaled-up and widespread adoption of demand response solutions are increased flexibility and reduced needs for conventional fossil-fuelled thermal generation, and thereby lower GHG emissions. Simultaneously, by decreasing total and peak electricity demand, demand response solutions can yield a reduction in VRE curtailment.
- **Providing economic incentives and market opportunities to small, decentralized assets.** The main barrier for aggregators to actively participate in ancillary services is often economic. In the Italian virtual power plants (UVAM) pilot project case study for example, the low activation of small, decentralized assets due to high energy bid prices and the business case reliance on balancing capacity remuneration was not yet competitive with conventional balancing resources. Like renewables, a small economic subsidy may be required to activate such flexibility resources. The case study also showed that many challenges still exist today for the participation of aggregators in ancillary service markets, including: (1) the lack of expertise to submit offers on

balancing service markets; (2) the cost of purchasing and implementing the technology to send data and manage activation orders at the high time-resolutions required, and according to the technical specifications of the transmission system operator; (3) challenges linked to the management and certification of metering data and subsequent economic settlement; (4) challenges on the side of system operators to know in real-time all available balancing resources and monitor their activation; (5) potential issues of market liquidity in the development of local markets in the distribution system network; (6) difficulties in the coordination between TSOs and DSOs to have access to flexibility resources and call their participation without generating issues to each other; (7) potential conflicts of balancing provision with renewable support schemes that incentivize maximizing generation volumes; (8) designing accurately the relationship between balancing service providers (BSPs) and balancing responsible parties (BRPS), especially defining their respective roles, responsibilities, and operational and financial liabilities in the energy dispatch outcome from the provision of balancing services; and (9) developing technology standards needed for implementing scalable solutions and to facilitate the prequalification process.

- **Considering specific local market regulatory frameworks.** From a policy perspective, the UVAM case study shows that a specific market regulatory framework focused on aggregated balancing service groups allowed the effective use of small, decentralised energy resources for ancillary services. However, the primary challenge today of this flexibility option is predominantly of an economic nature. To progress, all Member States should introduce measures to foster the participation demand response (and decentralised energy resources) in ancillary service markets (and in all electricity markets when technically feasible). From the EU level, a homogenisation of processes around ancillary service provision, including prequalification, technical requirements, minimum bid size, etc., could be valuable in avoiding a segmented implementation of ancillary service markets in each Member State. For local flexibility or congestion management markets, pilot projects such as UVAM can serve effectively as a "test and learn" phase to allow these flexibility markets to mature and, at a later stage, aim at defining a more complex and homogenous EU regulatory framework.
- **Improving demand response measures.** In the flexibility analysis (see chapter 3.2), the ways in which demand response measures can reduce VRE deficit situations and flexibility needs were quantified. Unlike cross-border interconnectors, demand response measures implemented in all European countries are not limited by the available generation and thus only depend on the amount of flexibility that demand can serve to the system. This form of flexibility is found to be especially relevant during hours of peak VRE deficits (i.e., generalised low VRE generation relative to demand). Despite the infrequent occurrence of peak VRE deficits, during those moments, interconnectors can barely improve the situation by moving electricity across bidding zones, as the main problem is a lack of VRE supply or, conversely, an excessive demand. Hence, demand response can be very effective to tackle peak VRE deficit situations (by reducing demand, especially since the peak VRE deficits are strongly correlated with the morning and evening peaks in electricity demand) and peak VRE excess situations (by increasing demand). Demand side response must be enhanced for a higher security of supply and a better integration of VRE resources in the European electricity system. Demand-side response helps decarbonisation by better integrating VRE and limiting the use of other flexibility resources such as from fossil fuel generation.

5.4 Storage flexibility

Energy storage is essential to integrate increasing shares of renewable energy generation and ensure security of supply. As such, energy storage will be a fundamental flexibility resource to keep the generation and demand in balance in the electricity system. Stabilising fluctuations in demand and supply by allowing excess electricity to be saved over different time periods, from fast storage in seconds to longer storage over days, will be a key asset in a future VRE-dominated and decarbonised energy system. An overview of relevant policies and measures for storage flexibility can be found in Annex 1 – EU policies and measures.

The following measure can be relevant to improve storage flexibility:

- **Ensuring the development and deployment of a variety of energy storage solutions.** Today, the main energy storage technology in Europe is pumped hydro power storage (50 GW as of 2023 (ENTSO-E, 2022d)). However, battery energy storage projects providing system services and/or managing hourly electricity fluctuations are on the rise. Additionally, various new technologies to store electricity are developing at a fast pace and could become market competitive in the not-too-distant future. These include gravity based storage systems (e.g.(Gravitricity, 2023), (Energy Vault, 2023)), gas pressure based storage systems (e.g. compressed air energy storage), inertia-based (flywheel), systems based on thermal energy (e.g. (MAN Energy Solutions, 2023), (Pielichowski, 2014)), etc. Furthermore, energy storage solutions can be enhanced through the integration with other energy vectors. For example, thermal storage can be enhanced in district energy systems, gas cavern storage in hydrogen systems and batteries in transportation. Having energy storage solutions focusing both on long-term (i.e., caverns) and short-term (i.e., batteries) flexibility can serve to ensure security of supply. As pointed out in the flexibility analysis of this report, different flexibility needs arise in different time scopes. We quantified daily (changes in hourly residual demand), weekly (changes in daily residual demand), and annual (changes in monthly residual demand). Each of these can be tackled with different energy storage solutions depending on their discharge duration (a function of capacity and energy available) and thus the shorter- or longer-term storage cycle.

6 List of abbreviations

Abbreviation	Name	Reference
ACER	Agency for the Cooperation of Energy Regulators	https://acer.europa.eu
ACP	Aggregation Control Platform	
aFRR	automatic frequency restoration reserve	
AI	Artificial Intelligence	
ARERA	Autorità di Regolazione per Energia Reti e Ambiente – Italian NRA	https://arera.it
BALK	Italy & Balkans	
BALT	Baltic countries	
BESS	battery electric storage system	
BI	British Isles	
BRP	Balance responsible party	
BSP	Balancing service provider	
CACM	capacity allocation and congestion management	
CCGT	Combined cycle gas turbine	
CEC	Continental Europe Centre	
CEE	Continental Europe East	
CEER	Council of European Energy Regulators	https://ceer.eu
CEF	Connecting Europe Facility	
CEN	Continental Europe North	
CENW	Continental Europe Northwest	
CES	Community Energy Scotland	
CfD	Contracts for Difference	
DER	Distributed energy resource	
DSO	Distribution System Operator	EU Directive 2019/944, Art. 2 (29)
DSR	Demand-side response	
EC	European Commission	https://ec.europa.eu
EB GL	Electricity Balancing Guideline	
EEA	European Environment Agency	www.eea.europa.eu
EEX	European Energy Exchange	https://eex.com
ENTSO-E	European Network of Transmission System Operators for Electricity	https://entsoe.eu
ETC CM	European Topic Centre on Climate change mitigation	
ESS	energy storage system	
EV	Electric Vehicle	
FCR	frequency containment reserve	
FRR	frequency restoration reserve	
HHEP	Haringvliet Hybrid Energy Park	https://group.vattenfall.com/press-and-media/pressreleases/2022/vattenfall-opens-energypark-haringvliet--a-combination-of-wind-solar-and-batteries
GHG	Greenhouse gas	
GJ	Gigajoule	
GMT	Greenwich Mean Time	

GW	Gigawatt	
GWh	Gigawatt hour	
HSO	Heat Smart Orkney	
IB	Iberia	
IC	interconnection	
ICT	Information and Communication Technology	
KFCGS	Kriegers Flak Combined Grid Solution	
kt, kton	Kiloton	
KW	Kilowatt	
KWh	Kilowatt hour	
LPG	liquid petroleum gas	
MIX	Mixed policy scenario for delivering the European Green Deal by the European Commission	
MIX-CP	Mixed policy scenario for delivering the European Green Deal by the European Commission – with current policies	
mFRR	manual frequency restoration reserve	
MVA	Megavolt-Ampere	
MW	Megawatt	
MWh	Megawatt hour	
NECP	National Energy & Climate Plan	
NEMO	Nominated Electricity Market Operator	https://nemo-committee.eu
NRA	National Regulatory Authority	https://www.acer-remit.eu/portal/ceremp
NSOG	North Sea offshore grid	
OEM	Original equipment manufacturer	
PCI	projects of common interest	
PJ	Petajoule	
PPA	Power Purchase Agreement	
PV	Photovoltaics	
REG	Regular policy scenario for delivering the European Green Deal by the European Commission	
RePowerEU		
RES	Renewable Energy Supply	
RR	replacement reserve	
REWDT	Rousday Eglisay & Wyre Development Trust	
REWIRED	Rousay Egilsay & Wyre Islands Renewable Energy Development	
SCA	Scandinavia	
SDAC	Single day-ahead coupling	https://www.entsoe.eu/network_codes/cacm/implementation/sdac/
SDE	Dutch sustainable energy transition subsidy scheme	
SIDC	Single intraday coupling	https://www.entsoe.eu/network_codes/cacm/implementation/sidc/
SMARD	Strommarktdaten – Electricity market data for Germany, by German NRA	https://smard.de
SMILE	Smart Islands Energy Systems	
SoS	Security of Supply	
TEN-E	Trans-European Networks for Energy	

TERNA	Trasmissione Elettrica Rete Nazionale – Italian TSO	https://terna.it
TIDE	Testo integrato del dispacciamento elettrico	
TSO	Transmission System Operator	EU Directive 2019/944, Art. 2 (35)
TYNDP	Ten Year Network Development Plan	
TWh	Terawatt hour	
VPP	Virtual Power Plant	
VRE	Variable Renewable Energy	
UVAC	Unità Virtuali Abilitate di Consumo Virtually aggregated DSR	
UVAM	*Unità Virtuali Abilitate Miste* Virtually Aggregated Mixed Units	
UVAP	Unità Virtuali Abilitate di Produzione Virtually aggregated generation	

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8 Annex

8.1 Annex 1 – EU policies and measures

Cross border cooperation

Regulation (EU) 2019/943 on the internal market for electricity of the European Parliament and of the Council of 5 June 2019 (EC, 2019f)

- Article 3 contains that customers must be able to benefit from market opportunities and increased competition on retail markets, and barriers to cross-border electricity flows must be removed.
- Article 6 balancing market: Relates to the reservation of cross-border capacity for balancing purposes, but this reservation may be limited. Transmission system operators coordinate with each other to ensure maximum use and efficient allocation of cross-zonal capacity across timeframes.
- Article 14: Shows the requirements for the bidding zone review process. The objective of the review is to ensure that bidding zones are configured in a way that maximizes economic efficiency and cross-zonal trading opportunities while maintaining security of supply.
- Article 17: The process for the allocation of cross-zonal capacity across different timeframes in the electricity market. Cross-zonal capacity refers to the amount of electricity that can be transmitted across borders between different countries or regions.
- Article 26: Capacity mechanisms must be open to direct cross-border participation by capacity providers located in another Member State. Member States must ensure that foreign capacity capable of providing equivalent technical performance to domestic capacities can participate in the same competitive process as domestic capacity.
- Article 49: An inter-transmission system operator compensation mechanism to ensure that transmission system operators are compensated for costs incurred because of hosting cross-border flows of electricity on their networks.

Directive (EU) 2019/944 on common rules for the internal market for electricity (EC, 2019e)

- Article 3 requires Member States to ensure that their national laws do not hamper cross-border trade in electricity. This means that barriers to trade, restrictions on the movement of electricity, or discriminatory practices, should be avoided.
- Article 16 establishes that Member States require enabling regulations for energy communities so that they are open to cross border participation.
- Article 58 deals with the development of regional cross border markets and appropriate cross-border transmission capacities to meet demand and enhance the integration of national markets and promoting effective competition and consumer protection in close cooperation with relevant authorities.
- Article 61: Refers to cross-border issues and emphasizes the need for regulatory authorities to cooperate and exchange information with each other on such issues. This includes the allocation of cross-border capacity, the development of new interconnections within and between regions, and the management of congestion across borders.

Directive (EU) 2018/2001 of the European Parliament on the promotion of the use of energy from renewable sources (EU, 2018a)

- Article 5: Opening of support schemes for electricity from renewable sources- The Commission shall assist Member States throughout the negotiation process by providing information and analysis, including quantitative and qualitative data on the costs and benefits of cooperation, as well as with guidance and technical expertise. The Commission may encourage or facilitate the exchange of best practices and may develop templates for cooperation agreements to facilitate the negotiation process.
- Article 12 - Regional cooperation: states that Member States must cooperate with each other, taking account of all existing and potential forms of regional cooperation, to meet the objectives, targets and contributions set out in their integrated national energy and climate plan effectively.
- Article 22: Renewable energy communities- Member States may provide for renewable energy communities to be open to cross-border participation. This means that individuals and entities from other EU Member States may participate in a renewable energy community in a different Member States, provided that the relevant national laws and regulations allow for such participation.

Regulation (EU) 2018/1999 on the Governance of the Energy Union and Climate Action of 11 December 2018 (EU, 2018c)

- Article 9 Draft integrated national energy and climate plans - Member States are encouraged to coordinate their energy and climate policies and measures with neighbouring countries to achieve a more effective and efficient implementation of the Energy Union objectives.

Interconnectors

Regulation (EU) 2019/943 on the internal market for electricity of the European Parliament and of the Council of 5 June 2019 (EC, 2019f)

- Article 32: ACER is responsible for monitoring and analysing the implementation of network codes and guidelines to ensure a sufficient level of cross-border interconnection open to third-party access.
- Article 36: the proposal that ENTSO-E submits to ACER for defining system operation regions must take into account the degree of interconnection and interdependency of the electricity system in terms of flows. This means that interconnectors will likely be considered when defining the system operation regions and deciding which transmission system operators and bidding zones are covered by each region.

Directive (EU) 2019/944 on common rules for the internal market for electricity (EC, 2019e)

- Article 61: Regional cooperation between regulatory authorities on cross-border issues- states that regulatory authorities shall cooperate at least at a regional level to enable an adequate level of interconnection capacity within and between regions to allow for development of effective competition and improvement of security of supply, without discriminating between suppliers in different Member States.

Directive (EU) 2018/2001 on the promotion of the use of energy from renewable sources (EU, 2018a)

- Article 3 - Binding overall Union target for 2030- sets a target of achieving a 15% electricity interconnection by 2030. This is aimed at increasing the technically feasible and economically affordable level of renewable energy in the electricity system. Member States are encouraged to work together to develop transmission and distribution grid infrastructure, intelligent networks, storage facilities and interconnections to achieve this target. The Commission will support this effort using Union funds, including financial instruments, to facilitate the development of these projects and programmes.
- Article 5 Opening of support schemes for electricity from renewable sources - Member States can allow participation in support schemes for renewable energy by producers in other Member States and must set indicative shares of newly supported capacity or budget allocation for these producers. These indicative shares are set at 5% from 2023 to 2026 and 10% from 2027 to 2030 or based on the level of interconnectivity. Member States can also require proof of physical import and limit participation to producers in Member States with direct interconnections. The Commission will assist Member States with cooperation arrangements and assess the costs and benefits of renewable energy deployment by 2025.
- Article 11 Joint projects between Member States and third countries- In order for electricity produced from renewable sources in a third country to be taken into account for the purposes of calculating the renewable energy shares of the Member States, an equivalent amount of electricity to the electricity accounted for must be firmly nominated to the allocated interconnection capacity by all responsible transmission system operators in the country of origin, the country of destination, and each third country of transit. The construction of interconnectors is also addressed in paragraph 5 of Article 11, which sets out the conditions under which Member States may apply for account to be taken of electricity from renewable sources produced and consumed in a third country in the context of the construction of an interconnector with a very long lead-time between a Member State and a third country.

Regulation (EU) 2018/1999 on the Governance of the Energy Union and Climate Action (EU, 2018c)

- Article 4 National objectives, targets and contributions for the five dimensions of the Energy Union- The Member States must take into account the 2020 interconnection target of 10% and indicators of the urgency of action based on price differential in the wholesale market, nominal transmission capacity of interconnectors in relation to peak load, and installed renewable generation capacity; also, each new interconnector must be subject to a socioeconomic and environmental cost-benefit analysis and implemented only if the potential benefits outweigh the costs.
- Article 5 Member States' contribution setting process in the area of renewable energy – each Member State shall take into account when setting its contribution for its share of energy from renewable sources in gross final consumption of energy in 2030. The level of power interconnection between Member States is an important factor that can affect the deployment of renewable energy, as it can facilitate the transfer of energy from one Member State to another and therefore support the development of renewable energy sources in regions where they are most abundant.
- Article 9 Draft integrated national energy and climate plans - The Commission's recommendations may also address the level of electricity interconnectivity that the Member State aims for in 2030, as referred to in point (d) of Article 4, taking into account

relevant circumstances affecting the deployment of renewable energy and energy consumption.

- Article 23 Integrated reporting on the internal energy market - the level of electricity interconnectivity that the Member State aims for in 2030, in consideration of the electricity interconnection target for 2030 of at least 15% and the indicators set out in point 2.4.1 of Section A of Part I of Annex I, as well as measures for the implementation of the strategy for the achievement of this level, including those relating to the granting of authorizations.

Supply side flexibility

Regulation (EU) 2019/943 on the internal market for electricity (EC, 2019f)

- Article 3 states that market rules must facilitate the development of flexible and sustainable electricity generation. This includes the integration of electricity from renewable energy sources and incentives for energy efficiency. These provisions can be interpreted as indirectly encouraging supply-side flexibility.
- Article 64 – derogations- article aims to ensure that derogations granted under this article do not obstruct the transition towards renewable energy, increased flexibility, energy storage.

Directive (EU) 2019/944 on common rules for the internal market for electricity (EU, 2019)

- Article 3 Competitive, consumer-centred, flexible, and non-discriminatory electricity markets- investments in variable and flexible energy generation, energy storage, and the deployment of electromobility or new interconnectors between Member States. By encouraging the development and deployment of these technologies, the regulation aims to increase the flexibility of the electricity supply side and enable a more efficient and sustainable use of resources.
- Article 32 Incentives for the use of flexibility in distribution networks - briefly mentions supply-side flexibility, such as the use of distributed generation and energy storage to provide flexibility services to the distribution system operator. The regulatory framework should ensure that DSOs can procure such services from providers of distributed generation, demand response, or energy storage, in a transparent and non-discriminatory manner.
- Article 58 - General objectives of the regulatory authority - include provisions aimed at promoting the integration of large and small-scale production of electricity from renewable sources and distributed generation in both transmission and distribution networks.

Regulation (EU) 2018/1999 on the Governance of the Energy Union and Climate Action (EU, 2018c)

- Article 22 Integrated reporting on energy security – encourages the increase flexibility objectives of the national energy system by deploying domestic energy sources, demand response and energy storage.

Demand side flexibility

Regulation (EU) 2018/1999 on the Governance of the Energy Union and Climate Action (EU, 2018c)

- (64) places demand response as an energy efficient alternative that should be considered before energy planning, policy and investment decisions, under the energy efficiency first principle.

Regulation (EU) 2019/943 on the internal market for electricity (EC, 2019f)

- Article 3 (e) states that market participation of final customers and small enterprises shall be enabled by aggregation of generation or demand response facilities to provide joint offers on the electricity market and be jointly operated in the electricity system.
- Article 3 (j) mandates that sustainable generation, energy storage and demand response shall participate on equal footing in the market.
- Article 18 requires that network charges shall not discriminate against aggregation nor create disincentives for demand response.
- Article 22 mandates that capacity mechanisms shall be open to all resources capable of providing the required technical performance, including demand side management.

Directive (EU) 2019/944 on common rules for the internal market for electricity (EU, 2019)

- Article 15 – Active customers -, requests Member States to ensure that final consumers are entitled to act as active customers in the market without being subject to disproportionate or discriminatory requirements or charges, directly or through aggregation, and participate in flexibility and energy efficiency schemes.
- In Article17 – Demand response through aggregation -, it is specified that Member States shall allow and foster participation of demand response through aggregation alongside producers in a non-discriminatory manner in all electricity markets, including ancillary services by TSOs and DSOs.
- Article 32 calls for national regulatory frameworks for distribution system operators to procure flexibility services (including congestion management) from distributed generation, demand response and energy storage in a non-discriminatory manner.

Directive (EU) 2012/27 on Energy Efficiency **(EU, 2012)** *amended by Directive (EU) 2018/2022* **(EU, 2018b)**

- Article 15.4 requests Member States to remove incentives in transmission and distribution tariffs that might hamper participation of demand response in balancing markets and ancillary services. Grid regulation and tariffs shall not prevent network operators or energy retailers making available system services for demand response measures. Network or retail tariffs may support dynamic pricing for demand response measures by final customers, such as time-of-use tariffs; critical peak pricing; real time pricing; and peak time rebates.

Storage flexibility

Regulation (EU) 2022/869 on guidelines for trans-European energy infrastructure (repealing Regulation (EU) No 347/2013) (Revised TEN-E Regulation) (EC, 2022l)

- Annex II: The EU has allocated funding to develop energy storage projects under the EU Innovation Fund. Large-scale energy storage facilities (connected at 110 kV or more) are also part of the eligible energy infrastructures of the new Trans-European energy infrastructure regulation.

Regulation (EU) 2018/1999 on the Governance of the Energy Union and Climate Action (EU, 2018c)

- Article 4 includes energy storage in the national objectives of Member States in the dimensions of research, innovation and competitiveness, energy efficiency, energy security and market integration.

Regulation (EU) 2019/943 on the internal market for electricity (EC, 2019f)

- It is stated in (62) that energy storages should be market-based and competitive and should not be owned by system operators (excluding integrated system storage systems like capacitors or flywheels).
- Article 3: market rules should encourage the development of more flexible and sustainable generation, as well as more flexible demand, which could include the use of energy storage to balance the grid. In addition, the principles state that market rules should incentivize long-term investments in a sustainable electricity system, energy storage being one example of such an investment.
- Article 3 (g) states that market rules shall deliver appropriate investment incentives for energy storage.
- Article 3 (j) mandates that energy storage should participate in the market on equal footing with sustainable generation and demand response.
- Article 6 addresses energy storage alongside other market participants in the context of balancing markets. It ensures non-discriminatory access to all market participants, including energy storage, for balancing services. It also acknowledges the need to accommodate the increasing share of variable generation and energy storage in the electricity system.
- Article 8 highlights the requirement for NEMOs (Nominated Electricity Market Operators) to provide products for trading in day-ahead and intraday markets that are small enough to allow for the effective participation of demand-side response, energy storage, and small-scale renewables. The minimum bid size of these products should be 500 kW or less, which would enable customers to directly participate in the market.
- Article 13: includes energy storage among the resources that can be redispatched. Specifically, it states that the redispatching of generation and demand response shall be open to all generation technologies, all energy storage, and all demand response, including those located in other Member States unless technically not feasible.

- In Article 15 on active customers, it is mandated that customers with energy storage facilities have the right to a grid connection, are not subject to double network charges for stored electricity or when providing flexibility services.
- Article 18 requires that network charges shall not discriminate against energy storage or aggregation.
- Article 22 mandates that capacity mechanisms shall be open to all resources capable of providing the required technical performance, including energy storage.
- In article 32, it is stated that energy storage should participate on equal foot with other decentralised energy resources (generation and demand response) in the provision of flexibility services to distribution system operators.
- Article 57 outlines that DSOs and TSOs shall cooperate with each other in order to achieve coordinated access to resources such as distributed generation, energy storage to support their specific needs.

Directive (EU) 2019/944 on common rules for the internal market for electricity (EU, 2019)

- Article 36 Ownership of energy storage facilities by distribution system operators - allows DSOs to own, develop, manage, or operate energy storage facilities if certain conditions are met. These conditions include the facility being a fully integrated network component and the regulatory authority granting approval.
- Article 42 Decision-making powers regarding the connection of new generating installations and energy storage facilities to the transmission system – proposes the TSO must establish transparent and non-discriminatory procedures for connecting energy storage facilities to the transmission system and cannot refuse a connection based on possible future network capacity limitations.
- Article 54 Ownership of energy storage facilities by transmission system operators - proposes the conditions under which TSOs may be allowed to own and operate energy storage facilities and the role of regulatory authorities in assessing the necessity and fairness of such arrangements.

Directive (EU) 2018/2001 on the promotion of the use of energy from renewable sources (EU, 2018a)

- Article 15 - Administrative procedures, regulations, and codes - Member States are required to establish simplified and less burdensome authorization procedures for decentralized devices, and for producing and storing energy from renewable sources.

8.2 Annex 2 – Solutions table to decarbonisation and security of supply

Table 8-1. Synthesis table of solutions to tackle existing and future challenges to decarbonisation and security of supply.

Challenges towards a decarbonised and secure power system	Solutions			
	Supply	Demand	Infrastructure	Market/Regulatory
Short-term fluctuations from VRE mismatching short-term demand inflexibility (daily cycles). An example is the duck curve from high solar PV penetration (Qingchun Hou et al., 2019).	Complementarity between VRE resource types across countries daily. **Study on wind and solar complementarity** Hybrid systems incorporating VRE generation, storage and/or PtX (behind-the-meter solution) **Case study Haringvliet Zuid hybrid plant** (Vattenfall, 2020) Virtual power plants (VPP) where generation is managed as a portfolio of assets (EU-SysFlex, 2019).	Demand-side response (DNV, 2022) **Case study Heat Smart Orkney** (Compton and Hull, 2022a) Flexible operation of PtX plants (ENTSO-E, 2022b)	Cross-border transmission capacity enabling sharing of resources and helping even out short-term fluctuations. **Case study Kriegers Flak** (Energinet, 2022) Short-term storage systems like BESS or CAES Boost infrastructure interconnections to balance supply and demand across Member States.	Provide incentives for demand-side response. Regulatory incentives to foster flexibility from VRE resources: increase the value of the electricity generated by wind and solar vs. incentivise maximising generation. E.g. California solar orientation incentives (amiller, 2014); Thor offshore wind support mechanism in Denmark with a spot price signal based on annual average prices to settle Contract-for-Difference support.
Medium-term fluctuations from VRE mismatching short-term demand variability (weekly cycles), e.g. weekly wind and demand (week/weekend) patterns (EC, 2019g).	Complementarity between VRE resource types across countries on a weekly basis. **Study on wind and solar complementarity** Hybrid systems incorporating VRE generation, storage and/or PtX (behind-the-meter solution) **Case study Haringvliet Zuid hybrid plant**	Demand-side response (DNV, 2022) **Case study Heat Smart Orkney** (Compton and Hull, 2022a)	Cross-border transmission capacity enabling sharing of resources and helping even out medium-term fluctuations. **Case study Kriegers Flak** Medium-term storage systems like pumped hydro.	Strengthen long-term markets, i.e., forward markets, PPAs, CfDs. Boost infrastructure interconnections in order to balance supply and demand across Member States.
Long-term fluctuations from VRE mismatching short-term demand variability (annual monthly/seasonal cycles), e.g., Seasonal variation of demand, wind and solar	Complementarity between VRE resource types across countries on a seasonal basis. **Case study VRE complementarity** Hybrid systems incorporating VRE generation, storage and/or PtX (behind-the-meter solution) **Case study Haringvliet Zuid hybrid plant**	Demand-side response **Case study Heat Smart Orkney**	Cross-border transmission capacity enabling sharing of resources and helping even out seasonal fluctuations. **Case study Kriegers Flak**	Strengthen long-term markets, i.e., forward markets, PPAs, CfDs. Besides the energy-only market, improve opportunities such as interruptibility schemes or other demand-side response schemes. Capacity Mechanisms may provide availability of flexible assets as well, but need to be carefully assessed as they could impact in the energy-only market. Boost infrastructure interconnections in order to balance supply and demand across Member States.

Challenges towards a decarbonised and secure power system	Solutions			
	Supply	Demand	Infrastructure	Market/Regulatory
Lower firm capacity available in the system with progressive decommissioning of conventional thermal power plants can endanger security of supply/adequacy.	Hybrid systems incorporating VRE generation, storage and/or PtX (behind-the-meter solution) **Case study Haringvliet Zuid hybrid plant** Virtual power plants (VPP) where generation is managed as a portfolio of assets	Interruptibility mechanisms (TERNA, forthcoming)	Storages participating in capacity mechanisms. Long-term storage of electrofuels that can be produced and stored in high VRE generation seasons and released and used to generate electricity in low VRE generation season (via hydrogen gas turbines, fuel cells). e.g. underground hydrogen storage (Green Hydrogen Hub Denmark, 2022) (HyStock, forthcoming)	Strengthen long-term markets, i.e., forward markets, PPAs, CfDs. Capacity Mechanisms may provide adequacy improvements as well but need to be carefully assessed as they could impact in the energy-only market. Boost infrastructure interconnections in order to balance supply and demand across Member States, (Government of Spain, 2022)
Increasing balancing service needs due to higher unpredictability of VRE expansion.	Hybrid systems incorporating VRE generation, storage and/or PtX (behind-the-meter solution) **Case study Haringvliet Zuid hybrid plant** Mixed (generation/demand/storage) aggregated assets (VPP) to participate in balancing and other ancillary services. **Case study UVAM** (TERNA, 2023a) Decarbonised dispatchable generation with ramping capabilities to meet speed of response from the specific services (primary, secondary and tertiary control). E.g. hydrogen-fired gas turbines (Mitsubishi Power, 2022a)	Mixed (generation/demand/storage) aggregated assets (VPP) to participate in balancing and other ancillary services. **Case study UVAM** Provision of system services from PtX plants (ENTSO-E, 2022b)	Mixed (generation/demand/storage) aggregated assets (VPP) to participate in balancing and other ancillary services [Ref UVAM, ref Tesla VPP]. Mixed (generation/demand/storage) aggregated assets (VPP) to participate in balancing and other ancillary services. **Case study UVAM**	Better access to balancing markets, especially in the short-term, also for RES, and with cross-border consideration
Decreasing inertia in the system due to decreasing share of synchronous generators vs. increasing share of asynchronous generators (wind, solar PV)	Wind and solar with advanced inverter capabilities. Tapping into electronic based resources for "fast frequency response" can enable faster response rates than traditional mechanical response from conventional generators, thereby reducing the need for inertia (Denholm et al., 2020) Hydrogen-fired gas turbines as renewable synchronous generation providing inertia to the system (GE, 2023)		Storage systems incorporating advanced inverter capabilities (Denholm et al., 2020) (Lin et al., 2020) Storage systems incorporating synchronous generators (Highview Power, forthcoming)	

Challenges towards a decarbonised and secure power system	Solutions			
	Supply	Demand	Infrastructure	Market/Regulatory
Grid bottlenecks in distribution networks		Demand-side response **Case study Heat Smart Orkney** (Compton and Hull, 2022a)	Grid expansion of distribution networks where decentralised energy resources are connected.	Local flexibility markets (DNV, 2022)
Investment in generation below the level of reliability standards due to the loss of profitability of conventional generation				Technology neutral capacity mechanisms: capacity markets, strategic reserves, capacity guarantees.
Increasing price volatility due to varying generation shares of VRE in the merit order curve.		Demand response services providing peak shaving options		Strengthen long-term markets, i.e., forward markets, PPAs, CfDs to hedge against short-term price volatility.
Stress on the renewable industry supply chain due to the increasing number of renewable projects globally.				Definition of clear national/European energy and climate targets for the industry to follow and make the adequate investments. Circularity with reduced use of some raw materials, development of local supply chain where possible with international partnerships.
Scarcity of critical minerals for renewable technologies and storage systems	Reusing/recycling of components and raw materials (iron, copper, etc.). Circular economy for renewable components. (Wind Europe, 2021)			
NIMBYism	Repowering of existing plants. (U.S. DOE, 2021) Advanced wind turbine models with higher capacity factors for the same wind resources. (IRENA, 2019) Marine energies: offshore wind away from land. (McMahon, 2018)			Adequate regulatory schemes for local communities where renewables are placed (e.g., compensation schemes, local investment or employment as part of criteria to award renewable project capacity).
Slow permitting				Simplify and accelerate the permitting process of new renewable projects: fast-track procedures, one-stop-shop, relaxing bureaucratic steps where unnecessary, increase resources in the administration of permits.