METIS Studies

Study S11

Effect of high shares of renewables on power systems

METIS Studies
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1. ABBREVIATIONS AND DEFINITIONS

1.1. ABBREVIATIONS

Abbreviation	Definition
BAU	Business-as-usual
CAES	Compressed air energy storage
CCGT	Combined-cycle gas turbine
CPO	Coal phase-out
OCGT	Open-cycle gas turbine
PHS	Pumped hydro storage
RES	Renewable energy source
vRES	Variable renewable energy source

1.2. DEFINITIONS

Concept	Definition
Residual load	Total load (i.e. hourly demand) less the generation from variable renewable power generation, i.e. the remaining demand that needs to be supplied by conventional generation units, storage or imports.

1.3. METIS CONFIGURATION

The configuration of the METIS model used to evaluate the impacts of the MDI policy measures is summarised in Table 1.

Table 1: METIS Configuration

METIS Configuration	
Version	METIS v1.1
Modules	Power system module
Scenario	METIS REF16-2030, EuCo30-2030
Time resolution	Hourly (8760 consecutive time-steps per year)
Spatial granularity	Member State

2. EXECUTIVE SUMMARY

Renewable power generation has reached important shares in the European power mix (30% in today's gross generation) and are likely to further increase to 50% or even more by the year 2030 due to technology cost decrease in a context of decarbonisation of the energy system. The bulk of this additional renewable generation will be wind and solar power, which feature variable natural resources and thus variable power output. The increasing dependence of electricity generation on non-dispatchable sources, will impact its operation and structure. To accommodate this new production, adequate flexibility technologies are required that are able to counterbalance the variations in order to keep supply and demand balanced at any time.

The objective of this study is to evaluate the impact of high shares of renewables on the EU power system in the year 2030 and to assess the associated impacts in terms of enhanced needs for system flexibility.

To get a better grasp of possible power system future, the EU system is analysed for three 2030 scenarios, featuring varying shares of renewable power generation. The assessment is realised by means of the EU power system model METIS. METIS simulates the hourly dispatch of all generation, storage and interconnection capacities, taking into account the capacity mix and demand of all individual EU Members States. The simulation covers all 8760 consecutive hours of the selected year.

The analysis of the impacts of high RES shares on the power system is realised by evaluating the residual load (which is the total demand less the generation from variable renewable power generation, i.e. the remaining demand that needs to be supplied by dispatchable generation units, storage or imports) and applying a set of predefined metrics to analyse the impact on the utilisation of selected power system components, such as storage units or interconnectors. The evaluation of the residual load is extended by the quantification of flexibility needs for varying shares of renewable generation in order to identify the main drivers.

The study reveals that increasing RES shares may result in a RES production surplus during an increasing number of hours throughout the year. In case of insufficient system flexibility (e.g. storage, interconnection, DSR), this surplus needs to be curtailed. The increasing production from PV and wind will increase the price volatility and lower the average price level at wholesale markets (also known as "merit order effect" when an increasing share of production is characterised by a low or even null variable production cost). At the same time, rising RES shares imply the increased utilisation of storage and interconnector capacities.

The assessment of flexibility needs sheds light at the extent to which flexibility solutions will be required in the future. Daily flexibility needs are primarily driven by PV generation, except for low PV shares which reduce daily flexibility needs. Weekly flexibility needs, in contrast, are triggered by wind power generation, given the stochastic character of wind generation. Seasonal variation in demand across the year and the RES share determine annual flexibility needs. Rising PV shares drive annual flexibility needs, given the reciprocal correlation between PV generation and power demand across the year, whereas wind power generation correlates with demand and this contributes to lower annual flexibility needs.

Nonetheless, the flexibility needs of a specific country depend on its individual national peculiarities. Hence, it is important to design tailor-made portfolios of flexibility technologies for each individual country. This design procedure needs to take into account all kinds of flexibility solutions (ranging from flexible power generation, over storage and interconnections to DSR) in order to determine the cost-optimal flexibility portfolio.

3. INTRODUCTION AND SCENARIO DEFINITION

3.1. INTRODUCTION AND STRUCTURE OF THE REPORT

National support policies, a significant reduction in investment costs as well as clear commitment and target setting by European and national policy makers have triggered important investments in renewable energies over the past years. Renewable energy sources (RES) are nowadays considered as a key element in the overall strive for decarbonisation, accounting today for a share of 17% in all final energy consumed. In terms of (gross) electricity generation, nearly 30% originate from RES, whereof 11%-points are delivered by variable renewable energy sources (vRES), such as solar PV and wind power.

The European Commission's EUCO30 scenario foresees a share for RES in power generation (RES-E) of close to 50% by 2030 and about 65% by 2050, up from about 30% in 2016 (E3MLab, 2016). Other scenarios project the RES-E share even higher, reaching levels above 80%.

Yet, the stochastic availability of the natural resources for solar and wind power implies that power production is variable over time and non-dispatchable. Thus, a rising share in electricity generation from variable renewables will have substantial impacts on the future electricity system. To accommodate the variable production, adequate flexibility technologies are required that are able to counterbalance the variations in order to keep supply and demand balanced at any time.

The objective of this study is thus to evaluate the impact of high shares of renewables on the future EU power system and the related rise in flexibility needs.

The following section provides a short introduction of the METIS model, applied to carry out the subsequent quantitative assessment, and the scenarios analysed. Chapter 4 provides some initial outlines on the design of the EU's 2030 power system under the different scenarios. Subsequently, the concept of the residual load is introduced (Chapter 5) and the impact of rising RES shares on the residual load and various power system components are analysed, applying a set of standardised metrics (Chapter 6). Finally, Chapter 7 sheds light on the relationship between vRES penetration and flexibility needs and provides an outlook on flexibility solutions and cost-optimal portfolios, building upon results from the Mainstreaming RES report[1] (Artelys, 2017). The study concludes with a short summary.

3.2. THE METIS MODEL

METIS is an on-going project initiated by DG Energy[2] for the development of an energy modelling software, with the aim to further support DG Energy's evidence-based policy making, especially in the areas of electricity and gas. The model is developed by a consortium (Artelys, IAEW, ConGas, Frontier Economics), which already delivered a version of METIS covering the power system, power markets, and gas system modules to DG Energy.

METIS is an energy modelling software covering in high granularity (in time and technological detail, as well as representing each Member State of the EU and relevant neighbouring countries[3]) the whole European power system and markets. METIS relies on

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[1] For the preparation of the *Mainstreaming RES* report, METIS was used in order to evaluate different flexibility solutions, design cost-optimal flexibility portfolios and quantify the related economic gains.

[2] See http://ec.europa.eu/dgs/energy/tenders/doc/2014/2014s_152_272370_specifications.pdf

[3] METIS covers the EU28 plus Norway, Switzerland, Serbia, Bosnia and Herzegovina, Montenegro and FYROM.

the Artelys Crystal Super Grid platform. This platform provides a graphical user interface (cf. Figure 1), optimisation services and scripting capabilities that allow the user to extend the software without writing compiled code.

METIS includes its own modelling assumptions, datasets and comes with a set of pre-configured scenarios. These scenarios usually rely on the inputs and results from the European Commission projections of the energy system, for instance with respect to the capacity mix or annual demand. Based on this information, METIS allows to perform the hourly dispatch simulation (for the length of an entire year, i.e. 8760 consecutive time-steps per year). The result consists of the hourly utilisation of all national generation, storage and cross-border capacities as well as demand side response facilities.

The uncertainties regarding the demand and vRES power generation dynamics are captured thanks to a set of 50 weather scenarios taking the form of hourly time-series of wind, irradiance and temperature, which influence demand (through a thermal gradient), as well as PV and wind generation. The historical spatial and temporal correlation between temperature, wind and irradiance are preserved.

Figure 1 - Snapshot of METIS' graphical user interface, highlighting the distinction of Member States

A DG ENER website dedicated to METIS[4] contains all the METIS Technical Notes providing the technical background information of the tool, as well as all METIS Studies so far being published. The studies present analyses produced for DG Energy policy experts to support their evidence-based policy making on themes such as market design, system adequacy, impact of PCIs, capacity remuneration mechanisms, etc.

3.3. SCENARIO DEFINITION

The assessment is carried out for three scenarios which are characterised by different levels of vRES penetration in the year 2030.

- The **Business-as-usual Scenario (2030-BAU)** represents the European Commission Reference scenario for 2030 (European Commission, 2016). It includes all policies and measures adopted at EU level and in Member States (MSs) by December 2014 and meets the 2020 but not the 2030 targets for RES deployment, energy efficiency and emission reduction. RES share in final electricity demand is about 42%, vRES is at 30% (cf. left part of Figure 2).

- The **Target Scenario (2030-Target)** represents the European Commission EUCO30 scenario. This scenario meets all 2030 targets, i.e. 40% GHG emissions

[4] https://ec.europa.eu/energy/en/data-analysis/energy-modelling/metis

reduction, 27% share of renewables in final energy demand (FED) and suggests a 30% energy efficiency target. The RES share equals about 50% of final electricity demand.

- The **Coal phase-out Scenario (2030-CPO)** is derived from the 2030-Target scenario, but assumes linear coal phase-out between 2015 and 2050, meaning that about 17 GW of coal and lignite capacities are removed compared to the 2030-Target scenario (cf. right part of Figure 2).[5] Coal-based generation is then replaced by wind and solar, applying the same country-specific ratios between PV and wind generation as under the 2030-Target Scenario, implying an increase of 66 GW in wind and solar PV capacities. All other parameters (e.g. interconnector capacities) remain the same as under the 2030-Target Scenario.

In addition, a **2020 scenario** is analysed, which serves as a proxy for the current situation and builds upon the European Commission Reference Scenario for the year 2020.

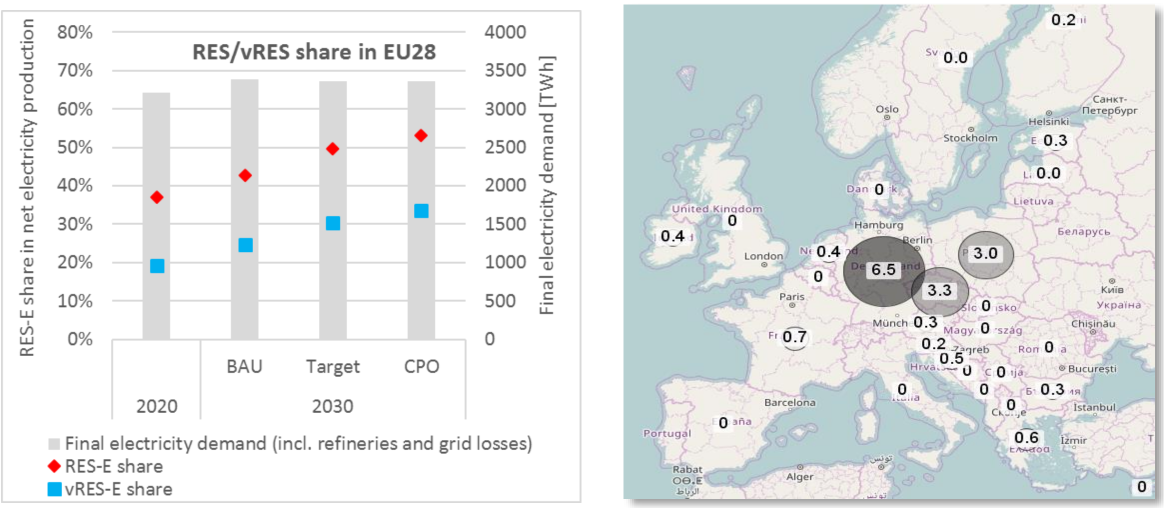

Figure 2 - RES share across the different scenarios (left) and coal capacities replaced by vRES generation under 2030-CPO Scenario, in GW (right)

Power demand varies a lot from one year to another because of varying weather conditions. Cold winters, for instance, imply a rise in power consumption in countries with large share of electric heaters. Power production is also directly impacted since wind, solar and hydro productions are linked to weather conditions. To appropriately consider the impact of varying weather patterns, three representative weather years are used in our scenarios: one normal year (2001) with temperature, wind and solar irradiance being close to average, one warm year (2002) and one cold year (2010). In the report, each indicator is calculated for all three weather years, but only the average value of the three is indicated.

4. Illustration of 2030's EU energy system

The majority of the currently published 2030 energy outlooks for the EU take a significant increase of renewable energy for granted. The cost of the associated technologies has dropped substantially over the last few years, and now all prospective scenarios for 2030 consider a large share of renewable energy in the electricity generation mix.

[5] Nearly 13 out of the 17 GW of closed coal and lignite plants are located in Germany, Czech Republic and Spain. While the German government has announced to draft a coal-phase out strategy in 2018 (that shall include an explicit target year for the completion of coal phase-out), Czech Republic and Poland did not announce any such plans so far (Europe Beyond Coal, 2017).

4.1. Share of variable renewable power generation in 2030

Two technologies are leading this high renewable penetration share in 2030: solar PV and wind onshore/offshore turbines. All three may be considered as nearly-mature technologies featuring competitive costs and a comprehensive deployment across Europe. But these two technologies have a major drawback compared to conventional generation plants like thermal units (coal, gas, or nuclear power plants): their production is not dispatchable and varies over time. The electricity generation depends on the weather, according to wind speed for wind turbines and solar irradiance for solar panels. A higher penetration of these variable renewable energy systems (hereafter referred to as vRES) will bring a cleaner energy generation but will have to come along with additional flexible solutions on order to ensure power system stability.

For the three given scenarios, vRES generation in 2030 is likely to cover more than a quarter of EU demand, compared to about 11% in today's power mix. Even the most conservative scenario (2030-BAU), where only policies and measures already adopted by the EU are included, foresees a vRES generation that covers 25% of the EU electricity production. Under the Target Scenario, vRES would cover 30% of the EU electricity production, and up to 34% if a gradual coal phase-out is considered (cf. Figure 3).

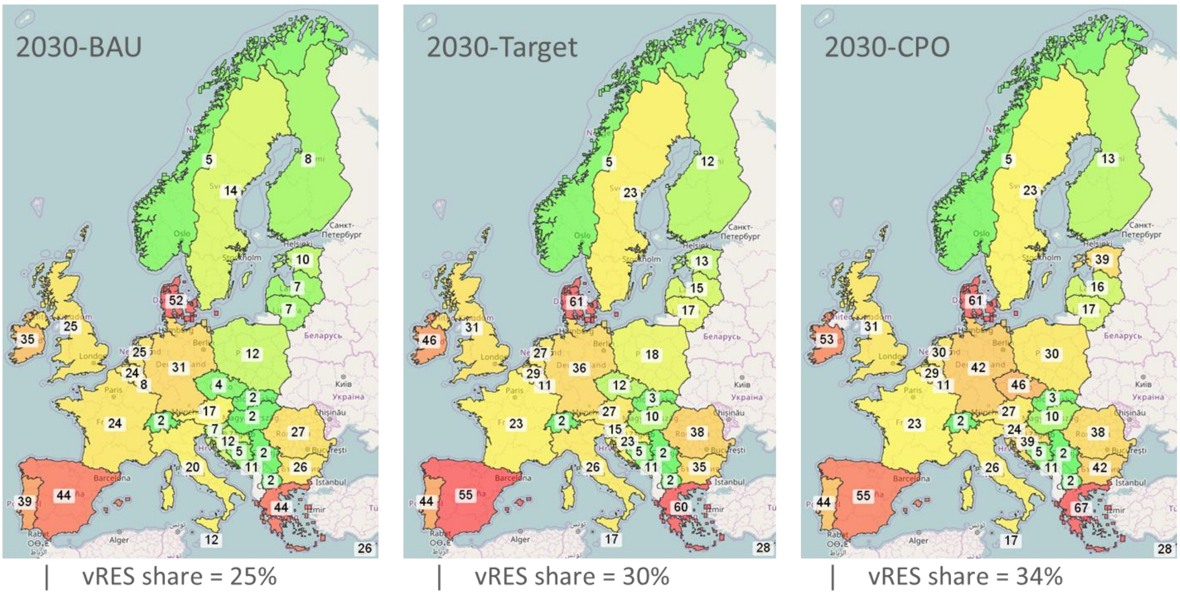

Figure 3 - Share of vRES in national demand (%)

However, vRES penetration is not the same across Europe but varies a lot from one country to another. In southern countries like Greece and Spain, almost a quarter of the yearly demand is met by solar PV generation. In northern countries, relying on the sun is not as interesting as in southern countries, so renewable production is mainly coming from wind energy, covering up to half of the yearly power demand in countries like Ireland or Denmark. Yet, wind capacities are deployed more evenly than solar across Europe, and southern countries are also taking benefit of wind energy. This combined solar and wind mix in southern countries lead to very high vRES shares: in the 2030-Target and 2030-CPO scenarios, the two technologies cover more than 50% of yearly power demand in Spain and Greece.

4.2. Variable renewables will jumble the generation mix in 2030

Wind and solar power feature nearly zero variable generation costs since operating wind turbines and solar panels almost does not require any fuel supply nor machine operators. Thus, on the wholesale market, they tend to outcompete conventional thermal units such as nuclear or coal plants and push them out of the market as the latter are characterised by higher variable costs due to purchase costs for fuel and, in case of fossil plants, CO_2 emission allowances.

Because solar and wind production is not constant, different weather conditions will lead to different generation mixes throughout the year. As solar production follows the daily cycle of solar irradiance, flexible units need to counterbalance the drop in solar production in evening and night time to satisfy power demand. Wind production instead is characterised by a more stochastic pattern with periods of production as well as of production-downtime that can last for several days in a row, requiring baseload units or long-term storage to cover power demand.

To understand how variable renewables affect the generation mix, the cumulative production is analysed, showing power generation assets in the order of rising generation costs: generators with lowest variable costs are at the bottom, and the most expensive ones at the top. The whole production for a given country, including exchanges, must match the power demand anytime.

4.2.1. Analysing a country with high wind share: Denmark

Two different 4-day periods in the 2030-Target scenario are analysed to assess varying wind production (Figure 4). The first one corresponds to a situation when the wind production is very low, and the second one when the wind production is very high (even exceeding the Danish power demand).

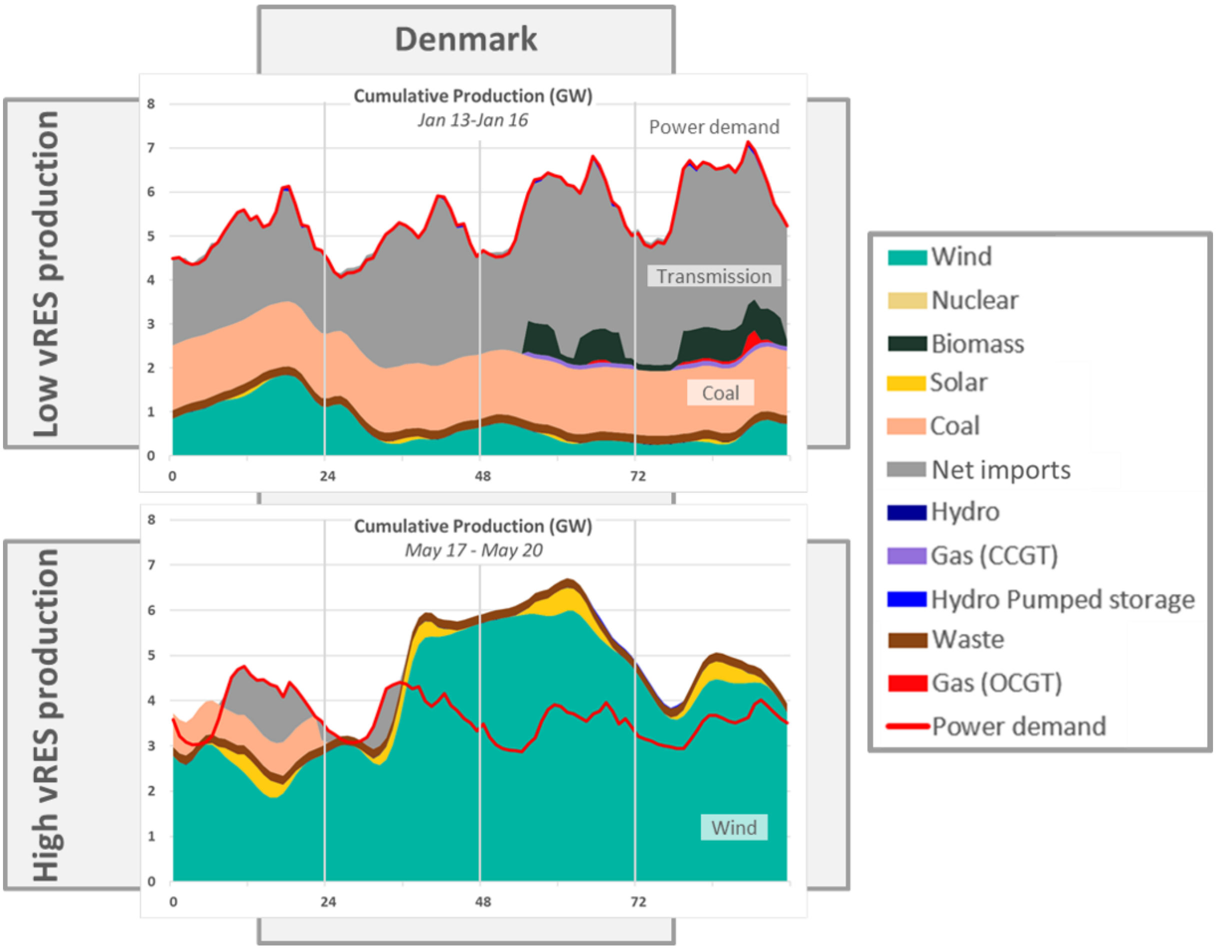

Figure 4 - Cumulative Production of Denmark in the 2030-Target scenario

In the case of low wind production, the demand in Denmark is primarily covered by conventional power plants (i.e. coal) and imports. Denmark is a well interconnected country and relies substantially on imports (primarily from Sweden and Norway) to cover its demand when renewable production is low. More than 50% of national demand can be met by imports in critical situations.

On the other hand, when wind production is very high, it covers a large part of the demand in Denmark, or even exceeds it for multi-day periods. In this case, power surplus can be stored or exported to neighbouring countries. However, if interconnections and storage capacities are used at their maximum, curtailment of the wind production surplus is compulsory to maintain the supply/demand equilibrium.

4.2.2. Analysing a country with a high solar PV share: Spain

Two different 4-day periods in the 2030-Target scenario are analysed to assess varying solar production in Spain (cf. Figure 5). Both situations are very different than the ones in Denmark with varying wind production. The daily cycle of solar production leads to distinct situations during day and at night time.

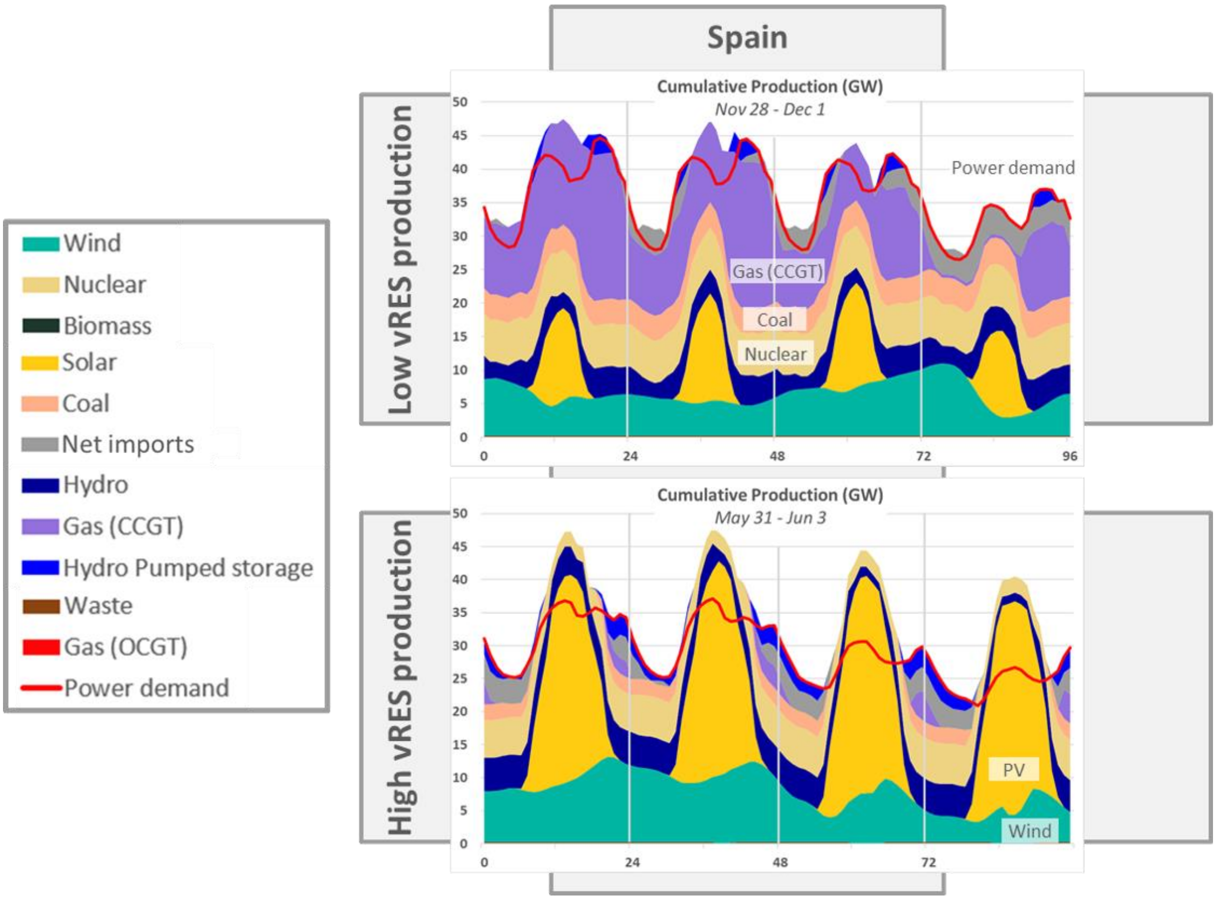

Figure 5 - Cumulative Production of Spain in the 2030-Target scenario

In winter, when the solar production is on average low, the power generated by solar PV covers part of the day-time demand. However, the overall vRES production cannot match the national demand, and Spain has to rely on base load capacities (such as hydro, nuclear or coal) and gas capacities[6].

In summer, when solar production is on average high, the situation is very different and changes throughout the course of the day:

[6] If prices in France are lower, gas production is substituted by imports.

- Around midday, solar production is at its maximum and exceeds power demand. During these hours, baseload capacities need to be shut-down, and the vRES surplus is exported or stored.

- The evening drop in PV production is balanced via flexible pumped hydro, imports and gas.

- During the night, baseload units go back on-grid run to cover a large part of the national demand.

5. ASSESSING THE RESIDUAL LOAD

5.1. INTRODUCTION OF THE CONCEPT OF THE RESIDUAL LOAD

As seen before, vRES penetration is not going to be uniform across Europe by 2030 but will show varying shares of solar PV and wind.

In order to obtain a better grasp of the impact of the variation of vRES on the power system and to define flexibility need indicators, the concept of *residual load* is introduced. It is defined as the hourly national demand less the production from vRES and describes the part of the national demand that needs to be met by dispatchable production units (such as coal, gas, nuclear), exchanges with neighbouring countries or storage units.

$$\boxed{\boldsymbol{residual\ load = power\ demand - vRES\ production}}$$

Looking at the cumulative of production for a given country allows to understand the profile of the residual load. For example, in Denmark (cf. Figure 6), the wind and PV production during the first day is lower than the power demand and the residual load is thus positive. Thus, additional flexible units are necessary to cover the demand: here coal power plants and imports from neighbouring countries are used. During the second day, vRES generation exceeds national demand implying a negative residual load. To face this production surplus, which needs to be balanced via flexible system components such as exports, electricity storage or demand side response.

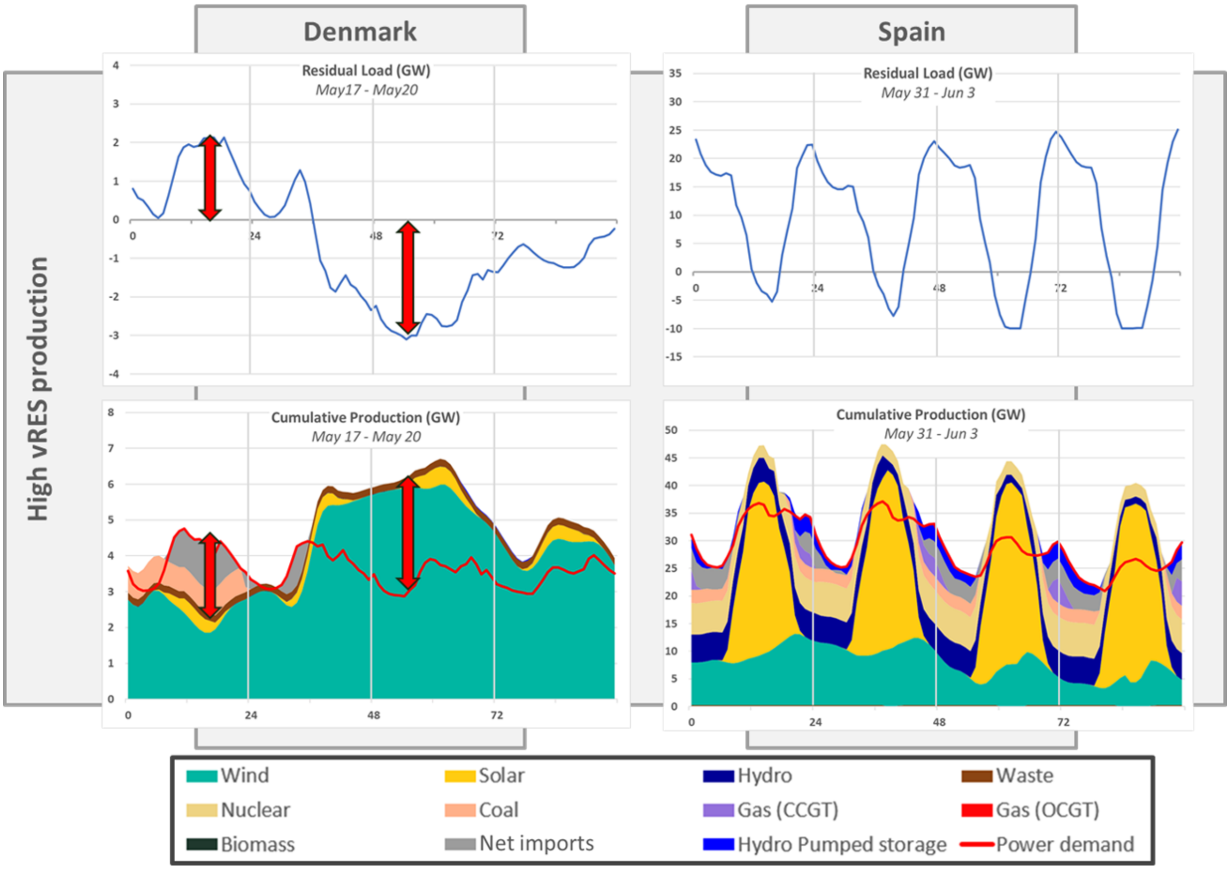

Figure 6 - Residual load construction for Denmark and Spain in the 2030-Target scenario

5.2. Description of the residual load in two exemplary countries

The residual load concept allows quantifying the amount of flexibilities required for a given country. The residual load patterns identified under the 2030 scenarios are symptomatic of the impact of higher vRES penetration on flexibility needs: the variability of vRES leads to a substantial fluctuation of the residual load and the occasional occurrence of negative values in hours of RES surplus. This is illustrated in the following for the two exemplary countries Denmark and Spain, showing the same 4-day excerpt as in Section 4.2.

5.2.1. The residual load in Denmark

In the 2030-Target Scenario, solar covers 2% of annual power demand in Denmark, wind 59%. During windless days, the residual load of Denmark is very similar to the national power demand (cf. upper part of Figure 7). It does not vary a lot in average between different days, but within a day flexible needs are necessary to match the power demand increase during the day.

However, a high share of wind production can lead to continuous periods of negative residual load lasting for several days, meaning that Denmark needs to export or store its renewable production surplus to avoid curtailment. Then conventional thermal plants such as coal that currently work as baseload units will have to shut down during the respective periods.

It is worth noting that from one week to another, wind power production may change significantly, meaning that Denmark needs a high level of flexible generation backup for situations of low wind, as well as a high capability to accommodate potential renewable surplus (in high wind situations), e.g. via storage or exports.

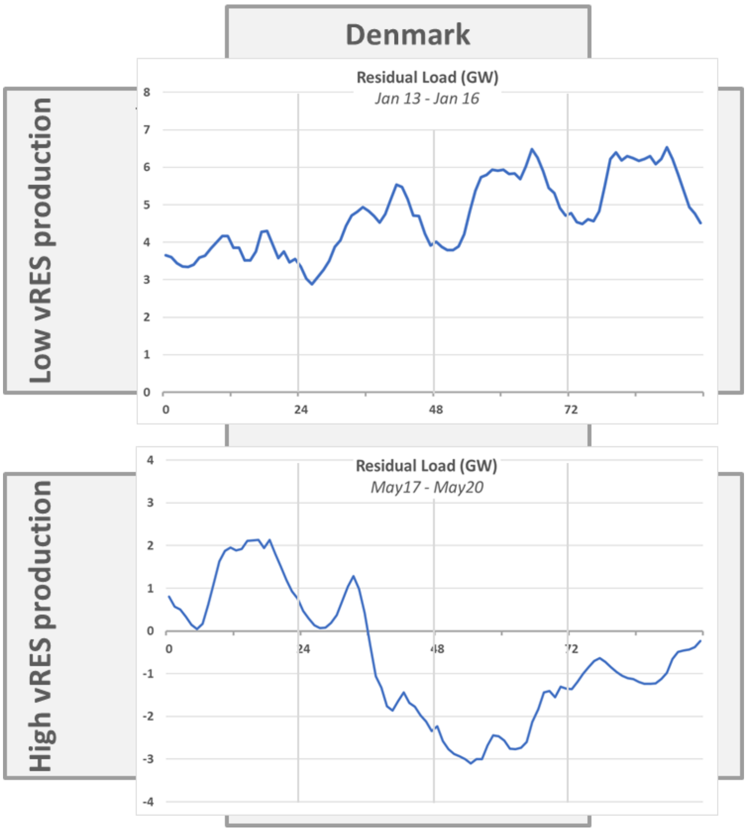

Figure 7 - Danish residual load in the 2030-Target scenario

5.2.2. THE SPANISH RESIDUAL LOAD

In Spain, solar covers 23% of annual power demand and wind 32% in the 2030-Target Scenario. Thus, the role of PV in the residual load is much higher than in Denmark. In winter times (cf. upper part of Figure 8), the moderate midday PV production decreases the residual load to a limited extent, leading to two residual load peaks per day: one in the morning and one in the evening.

During summer time instead, the massive PV production leads to a major residual load drop below zero around midday, but does not impact evening, night and early morning residual load. Thus, significant ramp rates appear between the sun rise and midday, and between midday and the sun set.

During winter time, the difference between the midday minimum and the evening peak is around 15 GW, while during summer this difference can exceed 40 GW. Hence, back-up power generation units need to be particularly flexible to cover the remaining demand, being able to run at full capacity during the night and to fully shut-down during the day. This flexibility requirement is much more important during summer than winter time. Yet, the residual load is characterised by a similar daily pattern, unlike the Danish example above.

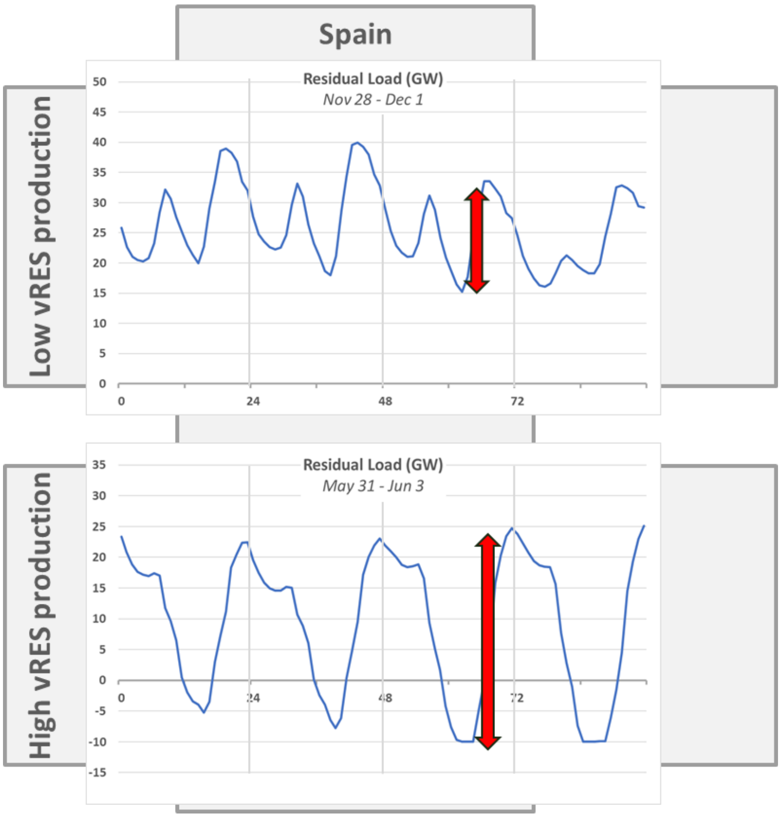

Figure 8 - Spanish residual load in the 2030-Target scenario

5.3. CHARACTERISE THE RESIDUAL LOAD

In order to provide a more holistic picture of the residual load, specific key performance indicators (KPIs) may be applied in order to summarise residual load evolution throughout the entire year.

5.3.1. SORTED RESIDUAL LOAD CURVE

The sorted residual load curve depicts the hourly residual load of the entire year, sorted in descending order. Since hours with the same residual load are gathered, it is easier to draw the impact of variable RES in similar situations. Maximum load, mid merit load situations and number of hours of RES surplus can be analysed at a single glance.

Figure 9 compares the sorted residual load curve for Ireland for the four scenarios, featuring in particular different shares of wind penetration. Residual load levels in the 2030-BAU Scenario exceed 2020 levels as demand increases by 13% between these two scenarios. The 2030-Target and 2030-CPO Scenarios also exhibit a higher power demand than in 2020, but this increase is offset and even reversed by the higher wind share.

In situations, when wind production is very low and demand very high (the first hours of the sorted residual load), all 2030 scenarios have a higher residual load than under the 2020 Scenario. Yet, the centre of the sorted load curve reveals that higher wind shares under the 2030-Target and 2030-CPO Scenarios lower the residual load. This implies that baseload capacities would experience a lower utilisation.

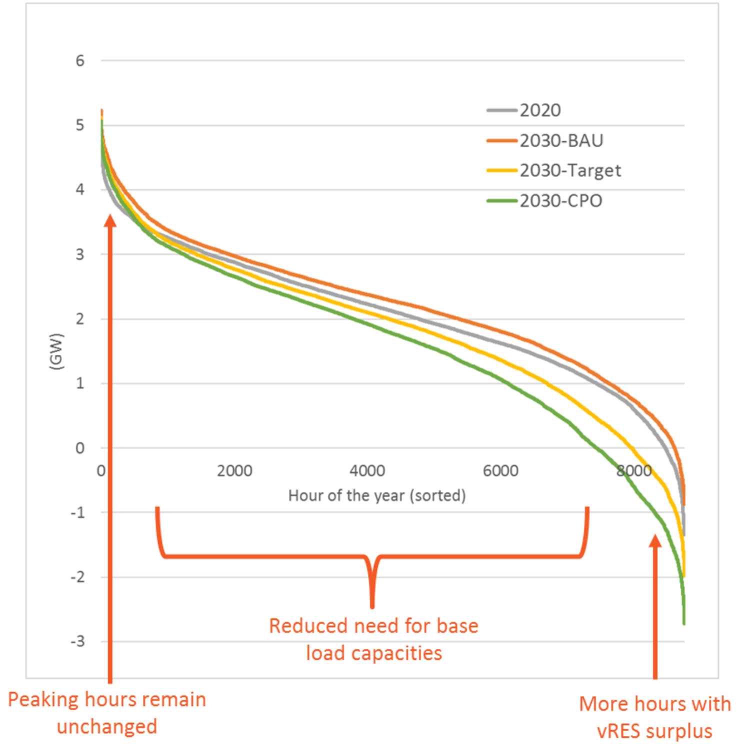

Figure 9 - Sorted residual load curve for Ireland

The rising vRES share across the scenarios also implies an increasing number of hours with RES production surplus. In Ireland, while the 2030-BAU Scenario would only know 150 hours of RES surplus, the 2030-CPO Scenario would have more than 1300 hours where RES production exceeds the demand, with up to 3GW of surplus.

5.3.2. HOURLY GRADIENTS

Rising vRES shares do not only lower the residual load level but also increase volatility in residual load throughout the day. A daily power demand profile is usually characterised by a demand increase during the day, especially during morning and evening hours. As PV production likewise follows a daily pattern, with a production peak around midday, a higher share of solar production will lead to a residual load trough during these hours. The impact of wind generation on the daily residual load profile is more difficult to isolate instead, given the stochasticity in power production.

The upper part of Figure 10 compares the average daily residual load for Spain across the different scenarios. The relatively low PV penetration in the 2020 Scenario leads to an almost flat residual load during the day. In contrast, 2030 scenarios have very high share of solar PV capacities, leading to an important decrease of the residual load during the day. Under the 2030-Target Scenario, the PV share is sufficiently high to make the average residual load drop below zero, meaning that a typical day of Spain production is characterised by a RES generation surplus around midday.

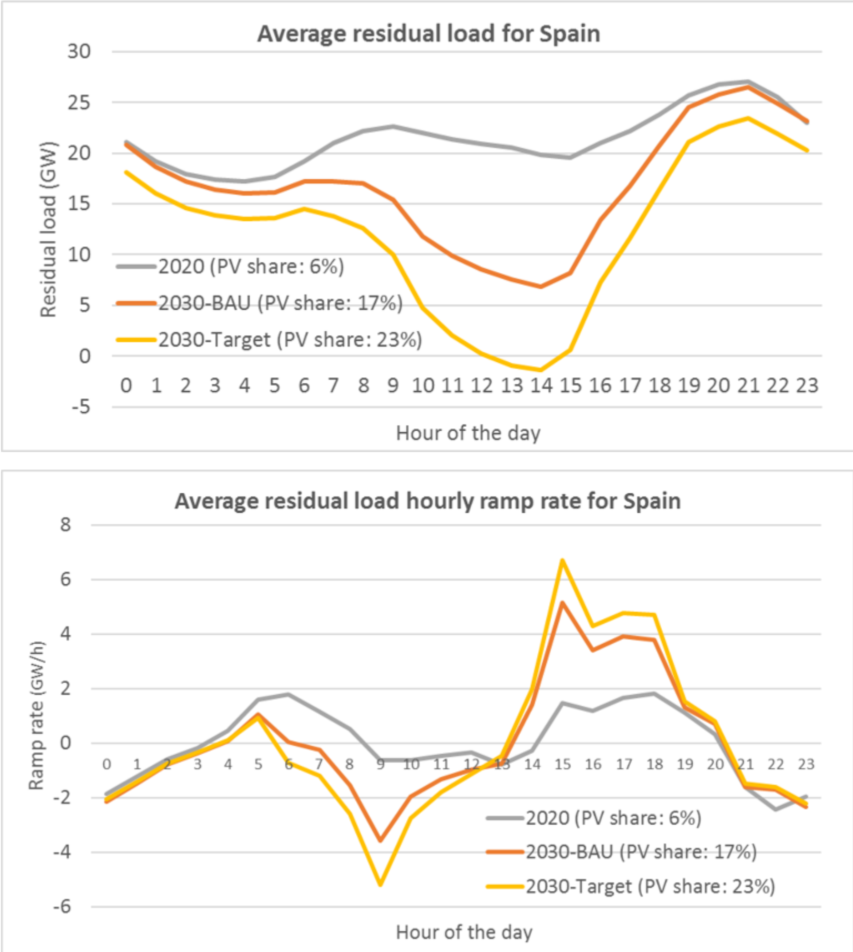

Figure 10 - Average residual load analysis for Spain

Hourly load gradients or ramp rates become substantially steeper because of the daily solar production peak. The average gradient of residual load between consecutive hours is shown for Spain in the lower part of Figure 10. While under the 2020 Scenario average hourly gradients remain below 2 GW, the 2030 Scenarios exhibit hourly changes in the residual load of up to 5 GW for the 2030-BAU Scenario, and almost 7 GW for the 2030-Target Scenario. That is, the Spanish power system needs to keep backup capacities ready that are sufficiently flexible to counterbalance the hourly variation in residual load during morning and afternoon periods.

In contrast to the previous average values throughout a day, Figure 11 illustrates the maximum hourly ramp rates to be expected under the 2030-Target scenario, meaning the steepest change in residual load between two consecutive hours occurring over the course of the year. In Germany, the hourly change in residual load reaches nearly 20 GW, almost a third of the average national load (65 GW), and more than a fifth of the peak demand (95 GW). Italy, Spain, France, Ireland and the UK feature maximum ramp rates exceeding 10 GW.

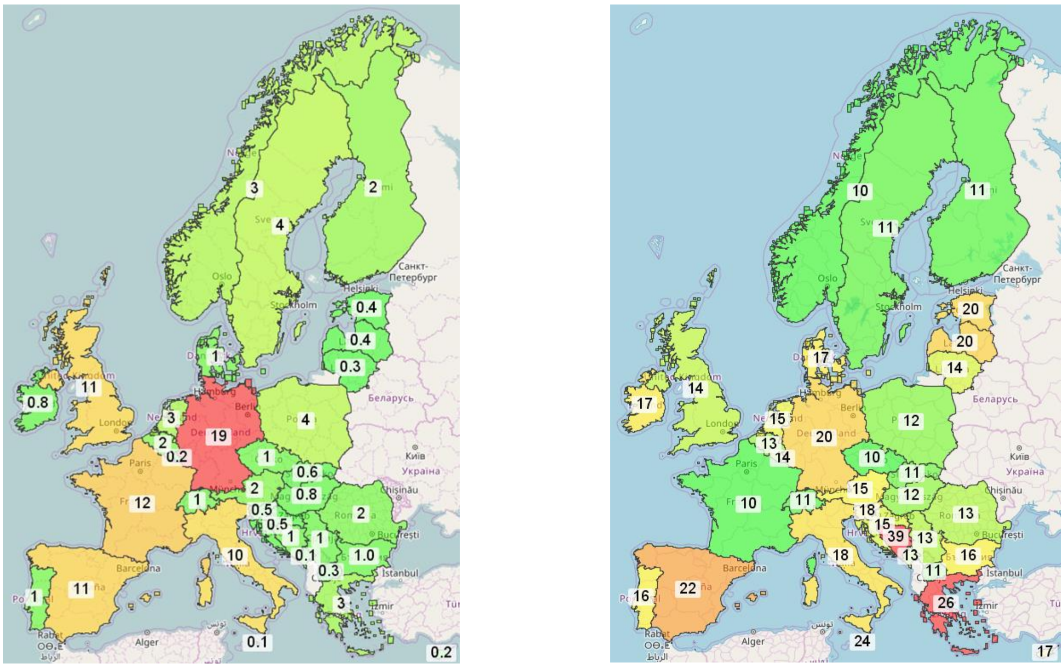

Figure 11 – Maximum hourly ramp rates across Europe for 2030-Target scenario (in GW, left) and as share of peak load (in %, right)

6. IMPACTS OF RISING vRES SHARES ON THE POWER SYSTEM

In the following we outline the impact of high shares of renewable power generation on existing assets of power generation, storage and interconnectors.

6.1. BASELOAD UTILISATION

RES generation is usually characterised by marginal generation costs close to zero, as they consist merely of operational costs, while fuel and CO_2 costs are null.[7] Thus, RES generation can be considered the technical option with lowest marginal generation costs in the power market[8], outcompeting all kinds of conventional generation assets. This implies that in future situations with relatively low demand, RES may supply the total demand and baseload capacities (such as nuclear or lignite plants) may be forced to shut down.[9]

Figure 12 indicates the hourly utilisation of Czech coal plants throughout 2030. Under the 2030-BAU scenario, coal power plants run non-stop, merely limited due to the reduced availability of capacities in summer months for reasons of maintenance.

In the 2030-Target scenario, coal capacities need to occasionally cut back production as higher PV and wind capacities reduce the residual load, thus pushing coal out of the market on selected summer days.

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[7] Biomass-based power generation is different from other RES technologies as the utilisation of biomass comes with the biomass purchase costs that lead to more elevated marginal generation costs.

[8] Marginal generation costs of conventional technologies depend very much on the carbon price. Under the EUCO30-2030 scenario and a carbon price of 27 €/t, nuclear plants feature costs of less than 10 €/MWh, lignite plants of about 45 €/MWh, coal plants of 50-60 €/MWh, combined-cycle gas turbines of 60-70 €/MWh and open cycle gas turbines of more than 80 €/MWh.

[9] Yet, there are situations in which conventional generation units continue to produce despite higher marginal generation costs, e.g. if they need to comply with reserve or heat supply obligations or if plant shut down and restart are costlier than the losses related to selling electricity at a price below their marginal generation costs.

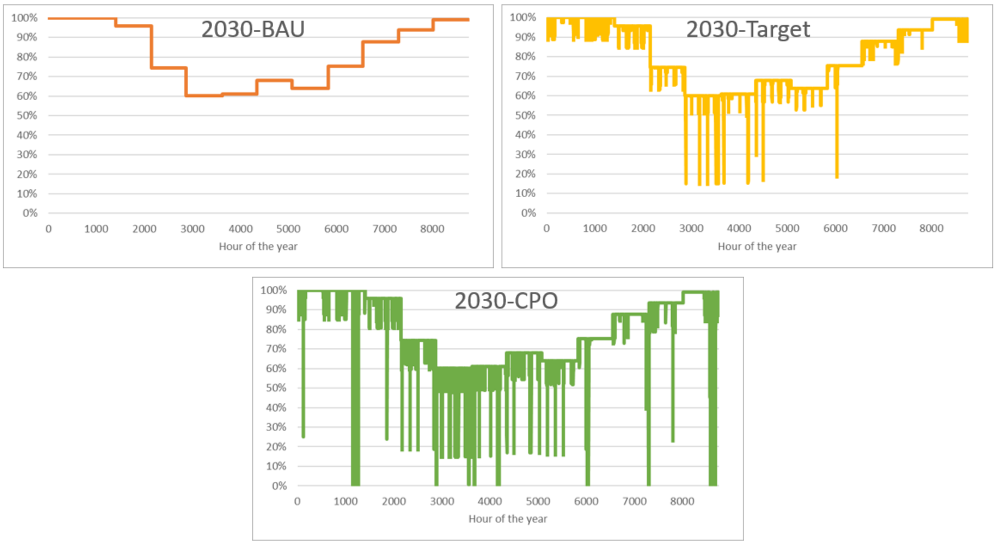


Figure 12 - Utilisation of Czech coal capacities throughout the year 2030 under three different scenarios

In the 2030-CPO scenario, the remaining coal capacities are regularly choked or even shut down at different moments throughout the year as RES power generation is periodically exceeding power demand.

This means that rising RES shares reduce the utilisation of baseload and mid-merit capacities and while operating costs increase due to recurring on/off states and enhanced ramping activities. These factors in combination with lower marginal generation costs (cf. next section) can impact their profitability.

6.2. MARGINAL GENERATION COSTS

In order to better grasp the impact of increasing RES shares on the market price levels at the national power exchanges, it is useful to plot the hourly marginal generation costs in descending order (cf. Figure 13 for Spain). Such a sorted cost curve indicates the number of hours that a price is equal or above a certain level. For instance, in the Spanish case in 2020 the market price exceeds 55 €/MWh in about 500 hours per year. It can further be noted that the overall level of 2020 marginal costs is lower than in 2030 due to lower energy carrier prices.

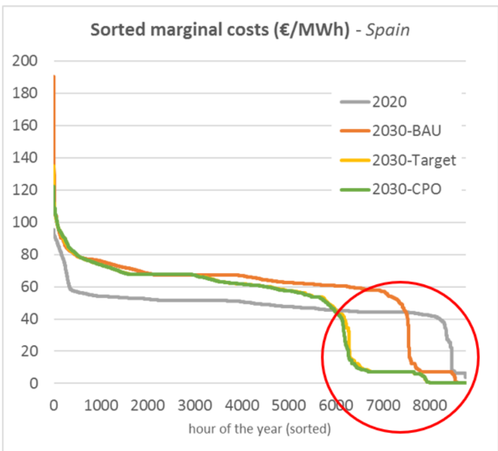


Figure 13 - Sorted marginal generation costs in Spain under different scenarios.

With rising vRES shares across the different 2030 scenarios, renewable power generation pushes mid-merit power plants out of the market (cf. previous section). Thus, generation units with lower marginal generation costs (such as vRES or nuclear) are more often setting the market price (see difference between the 2030 graphs highlighted in the red circle), hence lowering average prices and leading to an increasing number of hours with marginal generation costs of zero, which is similar to the variable generation costs of renewable power generation assets (except for biomass).[10]

This drop in average prices due to higher RES shares in combination with the reduced utilisation of conventional capacities makes it more difficult for conventional baseload and mid-merit power plants to recover their investment costs.

6.3. SHARE OF NON-SYNCHRONOUS GENERATION

Synchronous production capacities (such as thermal power plants) are essential to ensure system stability and a safe operation of the power grid. The mechanical inertia of the turbines used in conventional power plants is critical to keep the frequency of the power system close to its nominal value and prevent any deviations that could threaten the whole system stability. Wind and solar PV capacities on the opposite are non-synchronous generation systems and cannot provide such control on the system frequency if not specially equipped.

Between 2020 and 2030, the number of hours where more than half of the power production relies on vRES, will significantly increase. Figure 14 illustrates the number of hours during the year 2030, when the share of non-synchronous power production (i.e. wind and solar) exceeds 50% of total power productions. In countries featuring important vRES shares, such as Denmark, Spain or Greece, non-synchronous generation might exceed 50% of power production in one hour out of two, or even more often.

To ensure system stability, additional technology solutions might be required. These may include specially equipped RES generation plants (e.g. inverter-linked solar panels to deliver frequency response) or storage technologies.

[10] Negative prices occur in real markets in situations of production surplus. In such situations market participants do strategic bids at negative prices to ensure the continuous operation of their (baseload/CHP) plant and to prevent paying costs related to plant shut down / start-up. If such a situation of surplus occurs in METIS, these start-up costs are also taken into account. Yet, METIS' cost-minimisation approach chooses to curtail RES generation if the related opportunity costs are lower than the costs related to the shut-down and start-up of baseload capacities. Hence, variable generation costs of the different power generation assets do not reflect any strategic bidding and thus always remain positive, as do marginal generation costs.

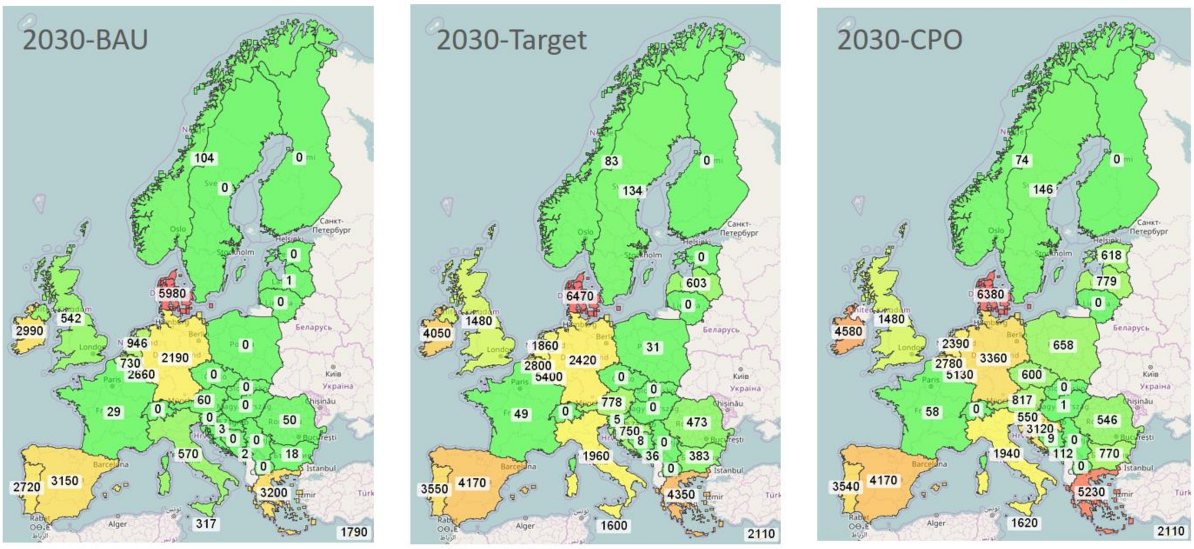


Figure 14 - Number of hours when the share of non-synchronous power production (wind and solar) exceeds 50% of total power production

6.4. Intensified utilisation of storage

As illustrated in Section 5.3, a rising RES share implies increased variability and ramp rates in the residual load. Storage systems, such as pumped hydro storage (PHS), represent one option to balance this increase in residual load variability, absorbing RES surplus by storing energy and counterbalancing a drop in RES production through power output.

Figure 15 illustrates the number of theoretical "full cycles" per year of PHS facilities, which is the mean ratio between generated electricity by PHS and maximum storage output. The utilisation of capacities planned for 2030 rises substantially with increasing vRES share.

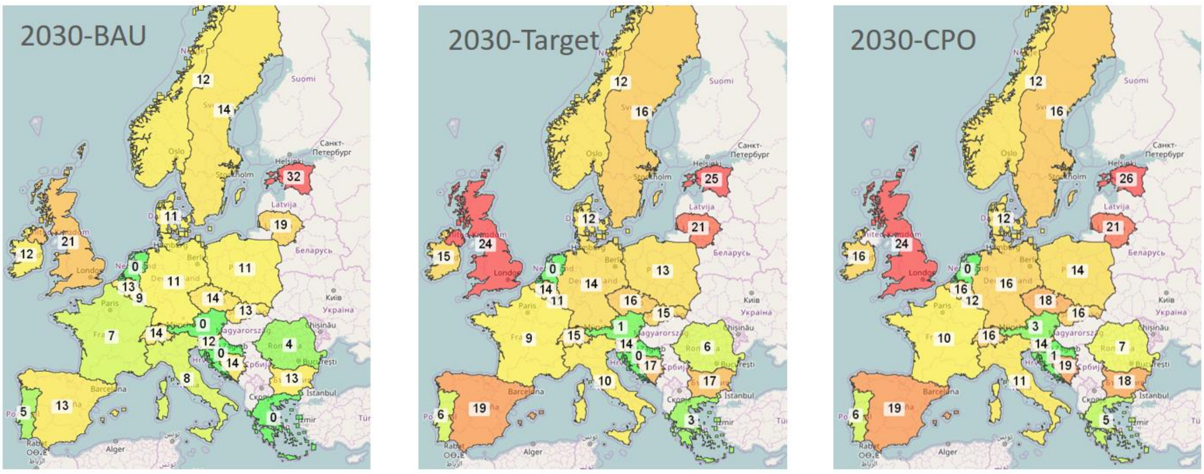


Figure 15 - Number of theoretical "full cycles" per year of pumped hydro storage

6.5. Increased cross-border flows

Another consequence of rising RES shares is the intensified cross-border electricity exchanges. As wind and solar power feature nearly zero marginal costs, they imply a decrease in wholesale market prices. If prices drop significantly in a given period in one country due to RES generation, a neighbouring country may replace its domestic power generation by cheaper imports. The cumulated power flows across all EU interconnectors[11] are thus likely to increase by about 20% compared to current levels (cf. Figure 16), reaching between 650 and 700 TWh in the three different scenarios.

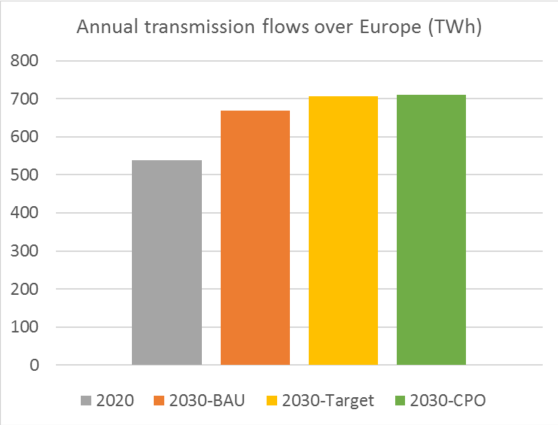


Figure 16 - Annual pan-European transmission flows

Increasing vRES shares do not only affect the utilisation of transmission capacities but may also impact the direction of power flows. Figure 17 illustrates an example: currently Spain is a net importer of French electricity, given the relatively low wholesale prices in France due to nuclear power generation. Yet, looking at July 4th under the 2030-Target Scenario, Spain will rely during summer night time on imports of cheaper power from France (based on nuclear power production). During day time instead, Spain features a vRES surplus and thus exports cheap renewable power to France and the rest of Europe. That is to say: interconnectors represent a major element to integrate vRES power generation, allowing to export electricity to neighbouring countries in case of RES surplus, and importing electricity in case of low RES production (if electricity is cheaper abroad).

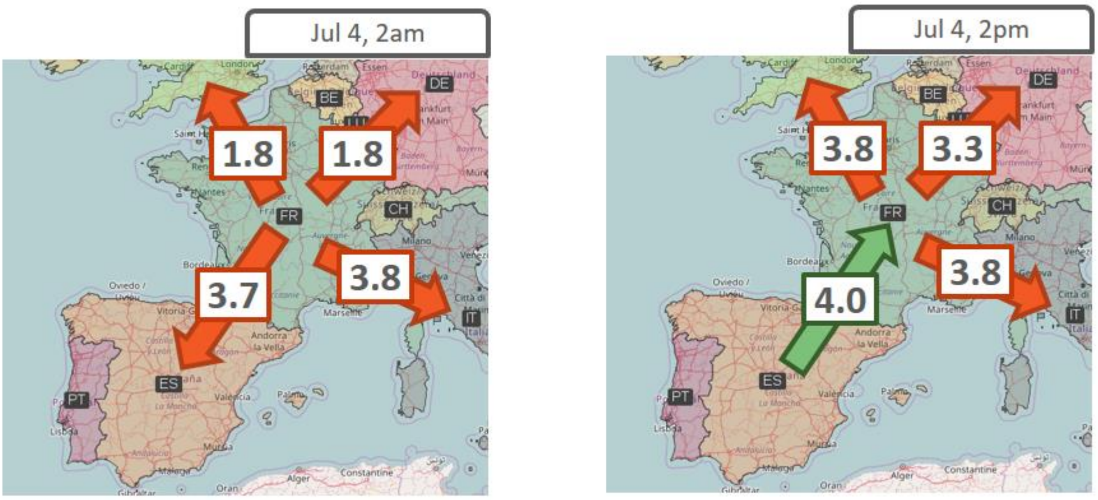


Figure 17 - Transmission flows between France and its neighbours on July 4th, at 2am (left) and 2pm (right), under the 2030-Target Scenario

6.6. CURTAILMENT DUE TO LACKING SYSTEM FLEXIBILITY

When vRES production exceeds national demand and vRES surplus cannot be offset via storage, export or raised demand (through Demand Side Response), it needs to be curtailed. More generally speaking, curtailment means restraining vRES production in case of lacking system flexibility for vRES integration. Looking at the 2030-Target Scenario reveals biggest quantities of RES production being curtailed in Spain (3.9 TWh) and Portugal (0.8 TWh) given their high share of PV and wind production and the limited

[11] A description of the interconnector capacities (which is the same across all 2030 scenarios) is given in the METIS Technical Note T1 (Artelys, 2016).

interconnection to the rest of Europe (cf. left part of Figure 18). This means that nearly 2.5% of all vRES generation is curtailed (cf. right part of Figure 18). Relatively important levels of curtailment are likewise attained in Latvia, Cyprus, Croatia and Ireland.

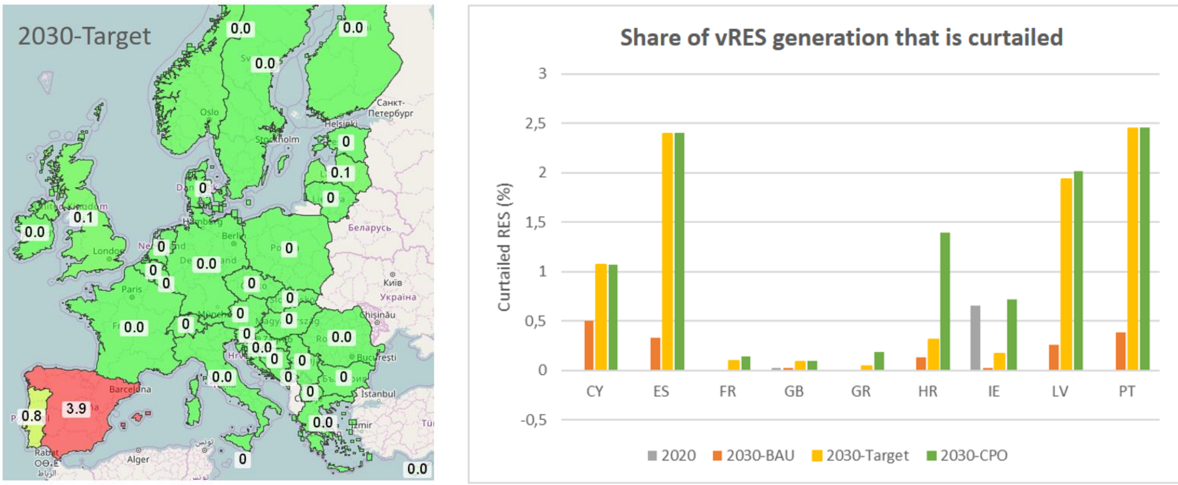


Figure 18 - Curtailment across Europe in absolute (left) in relative terms (right)

7. QUANTIFICATION OF FUTURE FLEXIBILITY NEEDS

Curtailment implies that parts of potential renewable power generation remain unused, as the system features insufficient flexibility to accommodate the respective amount of energy. Hence, it is important to obtain a comprehensive understanding of the extent to which rising shares RES generation increase flexibility needs in the power system and how to provide such flexibility as to limit curtailment to an economic minimum.

After a short introduction of a methodology to quantify flexibility needs at different time scales, flexibility needs are assessed for varying shares of wind and solar penetration for selected, exemplary countries in order to highlight their interdependency.

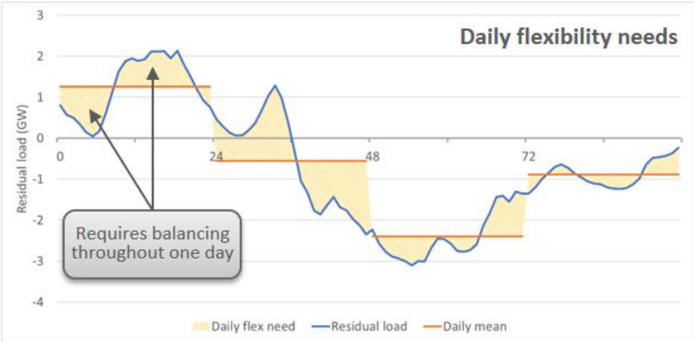
7.1. METHODOLOGY TO QUANTIFY FLEXIBILITY NEEDS

The French transmission system operator RTE has introduced a number of metrics that permit to evaluate national flexibility needs (RTE, 2017). These metrics are calculated on the basis of the residual load and facilitate the understanding of the extent to which rising RES shares increase these needs. Responding to these needs would lead to a fully smoothened net load that could be fully satisfied by baseload capacities. A large number of technical solutions exist to respond to flexibility needs at different time scales, cf. Section 7.3.1. Hence, flexibility needs are likewise distinguished regarding the time horizon. We distinguish daily, weekly and annual flexibility needs.

Daily flexibility needs are defined as the difference between the hourly residual load throughout a day and its daily average (cf. the shaded areas in the upper part of Figure 19). The result is expressed as a volume of energy per day (e.g. GWh/day). Summing up these daily (positive) differences over all 365 days of the year reveals the overall daily flexibility needs (expressed in GWh or TWh per year) one may respond to in order to obtain a residual load that is flattened out on a daily basis.

A similar calculation is realised in order to obtain the **weekly flexibility needs**, comparing the daily averages of the residual load (i.e. the residual load after having replied to all daily flexibility needs) with the mean residual load across each week (cf. lower part of Figure 19). Summing up the weekly flexibility needs of all 52 weeks gives the overall weekly flexibility needs.

Last, **annual flexibility needs** are determined as the cumulated difference between the weekly averages and the mean residual load across the entire year (not illustrated).



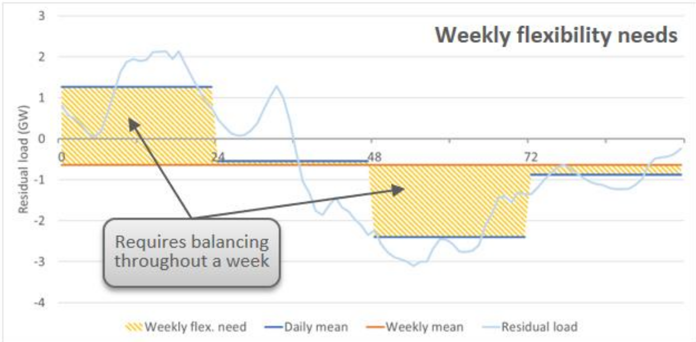


Figure 19 - Illustration of daily and weekly flexibility needs for a 4-day excerpt, based on the RES production period in Denmark introduced in Section 5.2.1

7.2. ASSESSMENT OF FLEXIBILITY NEEDS

In the following, flexibility needs are determined at the different time horizons for varying degrees of RES generation. That is, the country-specific hourly load curves and vRES generation profiles (for solar PV, wind onshore and wind offshore) are kept the same (i.e. same weather year), but the annual amount of RES generation is varied. Thus, RES generation profiles are scaled accordingly and provide different residual loads that serve as basis for the quantification of flexibility needs.

7.2.1. DAILY FLEXIBILITY NEEDS

Daily flexibility needs vary primarily as a function of the PV share, given the daily PV production cycle that is common to all installations independent of their site.

As PV production peaks usually coincide with midday demand, relatively low PV shares allow for residual load smoothing. This is for instance illustrated by the change of daily flexibility needs in Italy between the 2020 and 2030-BAU Scenarios, in the left part of Figure 20 or by the drop in flexibility needs shown in the right part of Figure 20, in particular for France.

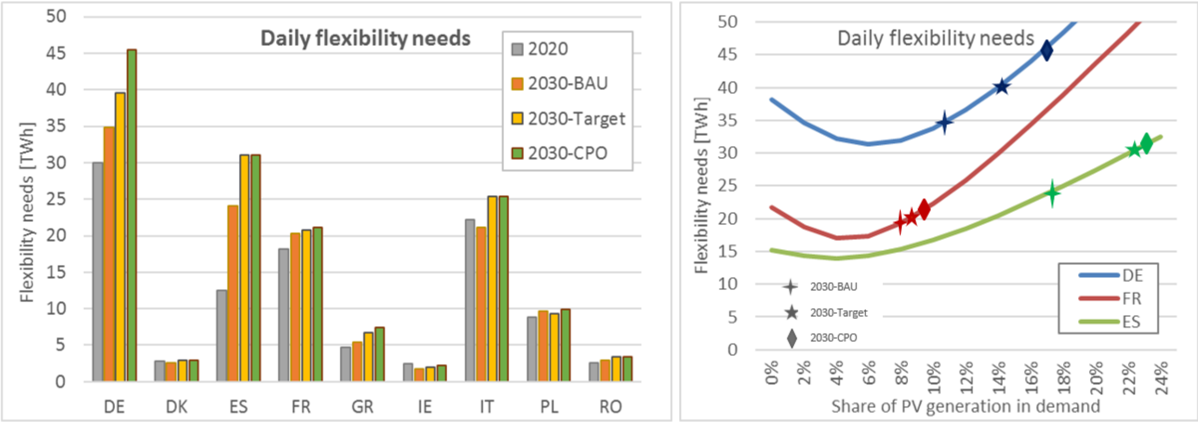


Figure 20 - Daily flexibility needs in selected countries across the different scenarios (left) and for varying shares of PV generation (right)

However, as soon as PV generation represents more relevant shares (exceeding 4 to 6% of total demand), the midday demand peak is flattened out and instead a residual load trough is created (in literature also often referred to as bathtub curve or duck curve, given the drop in residual load in the middle of the day, cf. Figure 21). This causes a substantial increase in daily flexibility needs, which can (for the given scenarios) in particular be observed in the countries featuring high vRES generation, such Germany, Spain, Greece and Italy (cf. left part of Figure 20).

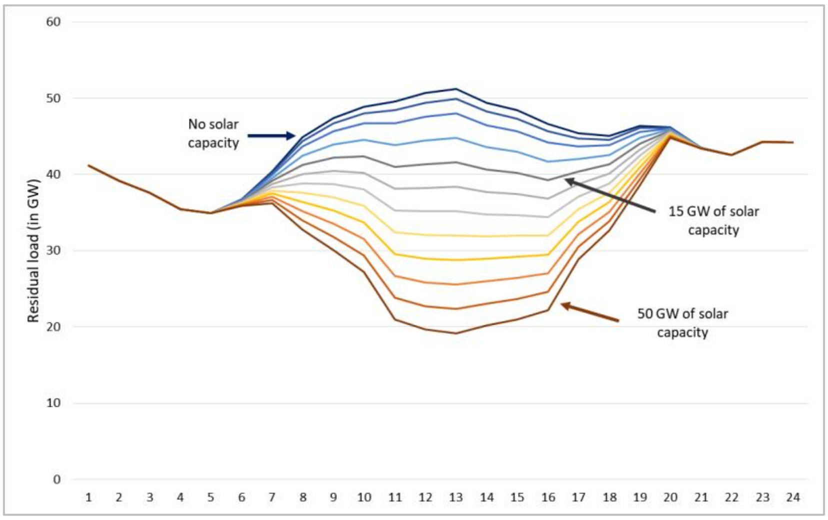


Figure 21 - Illustration of the demand (solid blue line) and impact of different levels of solar capacity deployment on the residual load of France under the 2030-Target Scenario (Source: (Artelys, 2017))

7.2.2. Weekly flexibility needs

Weekly flexibility needs are primarily driven by wind power generation, featuring more irregular, stochastic generation.[12] PV has a negligible impact.

Weekly flexibility needs are particularly high for countries like Germany, Spain, Ireland, Denmark (cf. left part of Figure 22), featuring substantial wind shares by 2030. In addition,

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[12] The present analysis assumes rather conservative capacity factors for wind power generation (cf. (Artelys, 2016) for further details). It can be assumed that in the future update wind turbine design may lead to more system-friendly power generation profiles, featuring higher capacity factors. See (Artelys, 2017) for more details on the related benefits.

it is to be noted that “from the first MW onwards” wind generation tends to increase weekly needs due to its stochastic production profile that rarely remains constant for much longer than a few days.

In countries with very low wind energy shares, weekly flexibility needs are driven by lower levels of demand during weekends (cf. the level of flexibility needs at 0% wind penetration in the right part of Figure 22).

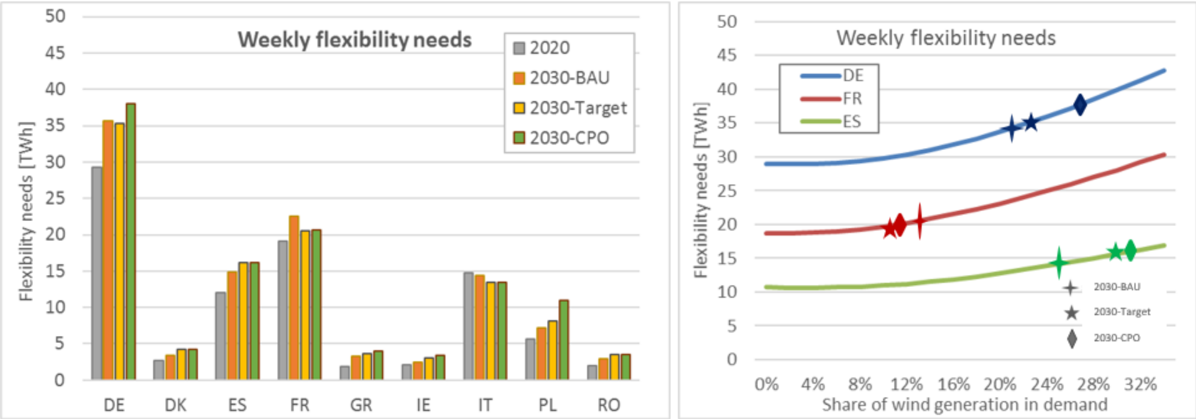

Figure 22 - Weekly flexibility needs in selected countries across the different scenarios (left) and for varying shares of wind generation (right)

7.2.3. Annual flexibility needs

Annual flexibility needs are particularly high for France, Germany, Italy. However, a closer look reveals at Figure 23 that needs in France are already today very high, due to the fact that French electricity demand is highly thermosensitive and demand in winter time is much higher than in summer time. Hence, RES penetration has only a marginal impact on the annual needs.

In contrast, Germany and Spain show an important rise in annual needs across the different scenarios. As bulk PV generation is concentrated in summer months and coincides with low demand levels, residual load drops significantly, whereas PV generation during winter only contributes to a limited extent to meet high demand, meaning the residual load level remain comparatively high. Hence the seasonal imbalance in residual load and thus annual flexibility needs are even further strengthened with rising PV shares (cf. left part of Figure 24).

Wind power production instead can reduce flexibility needs (cf. right part of Figure 24), as production is higher in winter than in summer season and thus correlates with the seasonal demand pattern of central and northern European countries.

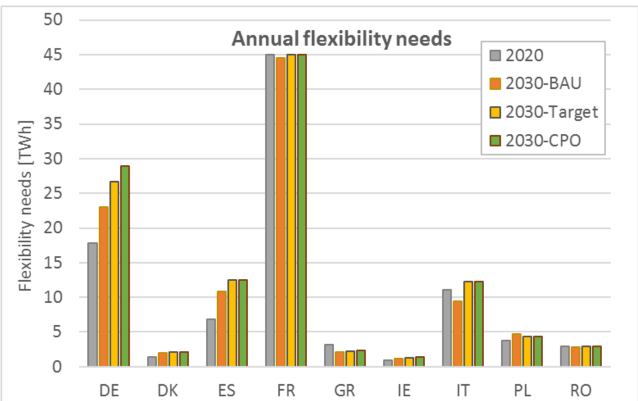

Figure 23 - Annual flexibility needs in selected countries across the different scenarios

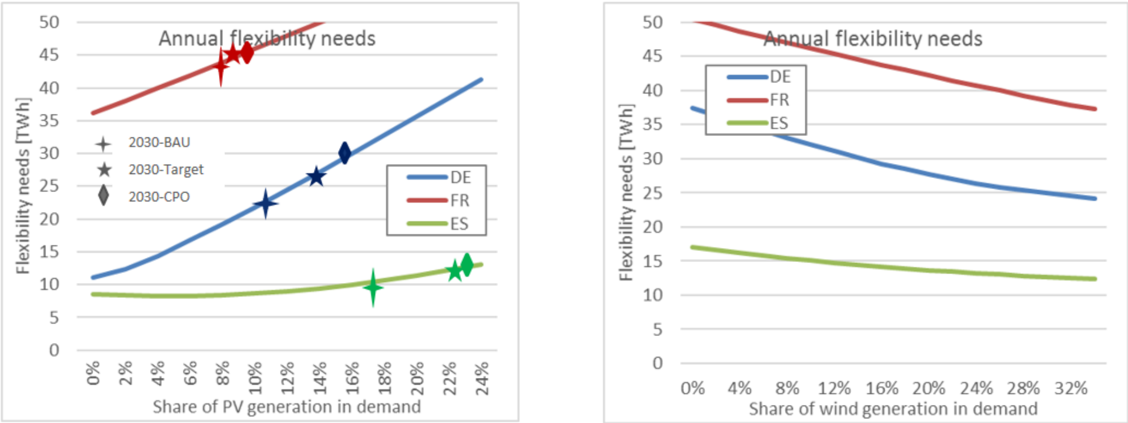

Figure 24 - Annual flexibility needs for varying shares of PV (left) and wind generation (right)

7.3. OUTLOOK: FLEXIBILITY SOLUTIONS AND PORTFOLIOS

Rising flexibility needs require a response through adequate technological solutions. While the assessment of such solutions is not the subject of this study, it deems useful to provide a short overview of potential solutions and their related benefits, by relying on the insights from the "Mainstreaming RES" project (Artelys, 2017). This project was carried out by Artelys on behalf of the European Commission (DG Energy) and assessed the least-cost flexibility portfolios for all EU Member States to facilitate a cost-efficient integration of high shares of renewables.

7.3.1. FLEXIBILITY SOLUTIONS

The objective of the different flexibility solutions is to smooth the residual load, which means counterbalancing variations in RES production and demand patterns. The different solutions vary in their ability to reply to the different time scales of flexibility needs. Typically, the following technologies are considered:

- **Flexible generation**: Gas turbines (OCGT) and combined-cycle gas turbines (CCGT) can be started on a very short notice and change their power output very quickly (high ramp rates). They serve as backup for situations when vRES production is low. Given their continuous availability throughout the year, they may reply to daily, weekly and annual flexibility needs, however featuring a relevant cost related to the purchase of gas and CO_2 emission allowances. Base-load capacities, such as nuclear plants, are likewise able to provide flexibility, considering retrofitting measures that enhance response time, production output gradients and starting times.

- **Storage**: Storage units allow on the one hand to increase demand in order to accommodate vRES surplus energy. On the other hand, they may release the stored energy in situations of scarce production capacity (e.g. low wind or solar irradiance). Typical storage technologies include pumped hydro storage (PHS, replying to daily and weekly needs) and compressed air energy storage (CAES, replying to weekly needs) as well as batteries (replying to daily needs).

- **Demand side response**: Two types of demand side response (DSR) are typically distinguished: (1) *Load shedding* represents the temporary shut-down of selected (usually industrial) electricity consumers, implying that the related energy service will not be delivered; (2) *Load shifting* means an occasional reduction in power consumption which is compensated at a later stage in time, still ensuring the full provision of the energy service (e.g. charging of electric vehicles, heat pump power consumption). Up to now, DSR is a relatively new concept and so far only applied on industrial consumers. It is primarily suitable to reply to daily flexibility needs.

- **Power-to-X**: The temporal or permanent electrification of selected end uses is usually referred to as Power-to-X and typically aims for their decarbonisation. Temporal electrification means that an end use may occasionally change from a given fuel to electricity[13], thus raising power demand in situations of vRES surplus or low demand. Permanent electrification increases system flexibility if the newly electrified consumers feature some flexibility in their consumption behaviour (i.e. the ability for load shifting) and may thus increase price elasticity of power demand. Usually, power-to-X applications are considered to reply to daily needs (except for power-to-gas-to-power or P2G2P solutions, which generate hydrogen or synthetic gas that can be reconverted at a later stage of the year into electricity, hence representing a long-term storage).[14]

- **Interconnections**: The enhanced interconnection of countries allows to better exploit the complementarity in the national power generation mixes, weather conditions (and thus vRES generation profiles) and demand profiles. It can be that one country shows important vRES surplus at a given moment, while its neighbouring country has a need for electricity. In such a situation, interconnectors facilitate the supply-demand balance by interconnecting several power systems. This may be beneficial to reduce flexibility needs at all time scales.

7.3.2. COST-OPTIMAL FLEXIBILITY PORTFOLIOS

The Mainstreaming RES project had for objective to evaluate the different flexibility solutions and to determine by means of the METIS tool the cost-optimal flexibility portfolio for each EU Member State (MS), taking into account each MS's peculiarities in terms of power mix, vRES share, vRES generation profile, power demand, geographical location and interconnection with neighbouring countries (based on the EUCO30 Scenario, i.e. the 2030-Target Scenario considered here).

Within the study, different scenarios were considered, with different flexibilities technologies at disposal to set up the cost-optimal flexibility portfolio. The base case only allows for investment in "conventional" flexibility solutions, i.e. gas-fired power production assets or the retrofit of existing coal and gas plants. The most ambitious scenario instead extended the scope of potential technologies for flexibility supply to DSR, storage units and interconnectors.

The study reveals that for Europe as a whole (including Norway, Switzerland and four Balkan countries), additional transmission lines, DSR, pumped hydro storage and batteries can substantially contribute to flexibility provision.

Related additional investments into these technologies (€1.47 bn annually) are nearly completely offset through avoided investments in gas power plants (€1.43 bn), in comparison with a scenario that only relies on gas/coal-based flexibility provision. Important savings through avoided power production costs from peak load power plants, related to the purchase of fossil fuels and CO_2 emission allowances lead to overall net savings of more than €2 bn annually.

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[13] E.g. a resistance heater in a district heating network which is occasionally used to replace the thermal boiler if the electricity price is particular low.

[14] Further information on the application of power-to-X solutions can be found in a number of forthcoming METIS studies addressing the optimal use of heat pumps (S6), the profitability of different power-to-gas configurations (S8) and the impacts of different charging strategies for electric vehicles on the power system (S13). All METIS studies and related documentation are available at (European Commission, 2018).

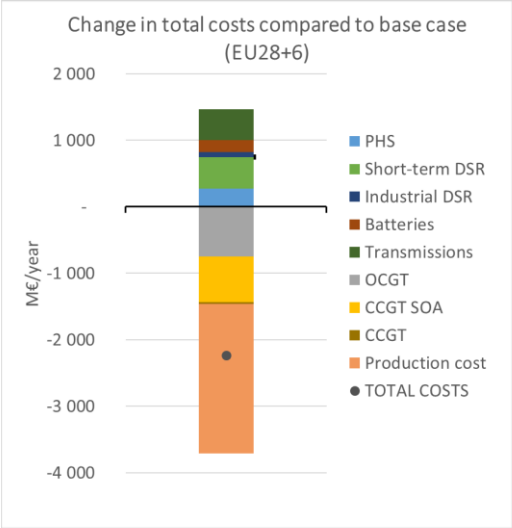

Figure 25 - Change in total costs compared to base case (Source: Mainstreaming RES)

8. CONCLUSION

This study has for objective to evaluate the impact of high shares of renewables on future power systems. The assessment was realised with the METIS tool, relying on a set of different scenarios for the year 2030, featuring shares of variable renewable power generation (i.e. solar and wind) between 25% and 34%.

The study reveals that increasing RES shares may result in a RES production surplus during an increasing number of hours throughout the year. In case of lacking system flexibility (e.g. storage, interconnection, DSR), this surplus needs to be curtailed.

The analysis shows that the variable production character of PV and wind generation will increase the price volatility at wholesale markets. Due to the nearly zero variable costs of power generation, RES further impact wholesale markets by pushing conventional generation capacities out of the market and lowering the average price level (also known as "Merit order effect"). This may affect the profitability of current and future investments in power generation and storage assets.[15]

Finally, rising RES shares imply the increased utilisation of storage and interconnector capacities. Yet, the previous observations make it obvious that additional flexibility measures might be required in order to minimise curtailment and ensure system stability.

In order to understand the extent to which flexibility solutions will be required in the future, a detailed assessment of flexibility needs at different time scales was carried out.

It turns out that daily flexibility needs are primarily driven by PV generation. While low PV shares reduce daily flexibility needs as they help to reply to the daily demand peak, high PV shares create a residual load trough at midday that requires balancing through dedicated flexibility solutions.

Weekly flexibility needs, in contrast, are triggered through wind power generation. Given the stochastic character of wind generation, adding wind capacities to the power system

[15] A detailed analysis of the related impacts on revenues from market participants is realised in METIS study "Wholesale market prices, revenues and risks for producers with high shares of variable RES in the power system" (S14, forthcoming).

directly implies an increase in flexibility needs, occurring from situations when no or less wind is available.

Last, seasonal variation in demand across the year and the RES share determine annual flexibility needs. Rising PV shares drive annual flexibility needs: PV generation is highest in summer season, when demand is relatively low (at least in most Central and Northern European countries) but low in winter season, when demand is high, thus increasing the imbalance of residual load between the two seasons. In contrast, seasonal variation in wind power generation correlates with demand meaning that rising wind shares contribute to reduced annual flexibility needs.

Yet, the flexibility needs of a specific country depend on its individual national peculiarities. Hence, it is important to design tailor-made portfolios of flexibility technologies for each individual country. This design procedure needs to take into account all kinds of flexibility solutions (ranging from flexible power generation, over storage and interconnections to DSR) in order to determine the cost-optimal flexibility portfolio.

9. References

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