Mainstreaming RES

Flexibility portfolios

Design of flexibility portfolios at Member State level to facilitate a cost-efficient integration of high shares of renewables

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Executive Summary

Context and objectives of this report

Working towards a less carbon-intensive electricity sector is one of the key objectives of the Energy Union strategy. In order for the share of energy production from renewable sources to reach 27% by 2030, as is targeted by the European Union, the deployment of variable renewable energy generation technologies such as solar and wind power will have to continue growing at a steady pace. In particular, it is estimated that around 50% of the electricity will have to be generated by renewable energy sources (RES-e) by 2030, compared to around 30% nowadays.

The integration of a large share of variable RES-e is not without challenges. First, their production is variable, meaning that the system needs to include technologies that have the ability to ramp up or down sufficiently quickly so as to maintain the balance between supply and demand at all times. Second, their production is difficult to forecast well in advance, leading to challenges in terms of system adequacy. One should indeed account for the contribution of variable renewables when performing system adequacy assessment, and take into account the complementarities that exist between national energy systems at the regional level in order not to overestimate investments.

As part of the "Clean Energy for All Europeans" package of policy proposals, the Commission has proposed a governance mechanism based on integrated National Energy and Climate Plans (NECPs). Draft NECPs are to be prepared by Member States by 2018. In particular, Member States are required to set national objectives with regards to flexibility and adequacy, and to report on measures to increase the flexibility of their energy systems.

The objectives of this report are to provide assistance to Member States by setting out a framework which can be used to evaluate the needs for flexibility as the share of variables RES-e increases, to identify and characterise flexibility solutions, and to design optimal flexibility portfolios that take into account the specificities of the national electricity systems, as well as the potential synergies that can emerge from a cooperation among Member States.

The report provides links and references to publicly available publications and datasets that can be exploited by Member States, or other entities, when evaluating the local needs for flexibility and how different solutions can be combined to form an optimal flexibility portfolio.

Finally, the results of applying the framework to the METIS EUCO30 scenario are presented. Three options are considered, which differ in terms of the set of flexibility solutions that are available. By comparing the results of the options, we highlight the role demand-response, storage and interconnectors can play in the provision of flexibility.

Main findings

The recommended framework is organised as a three-step process, and is illustrated by Figure 1.

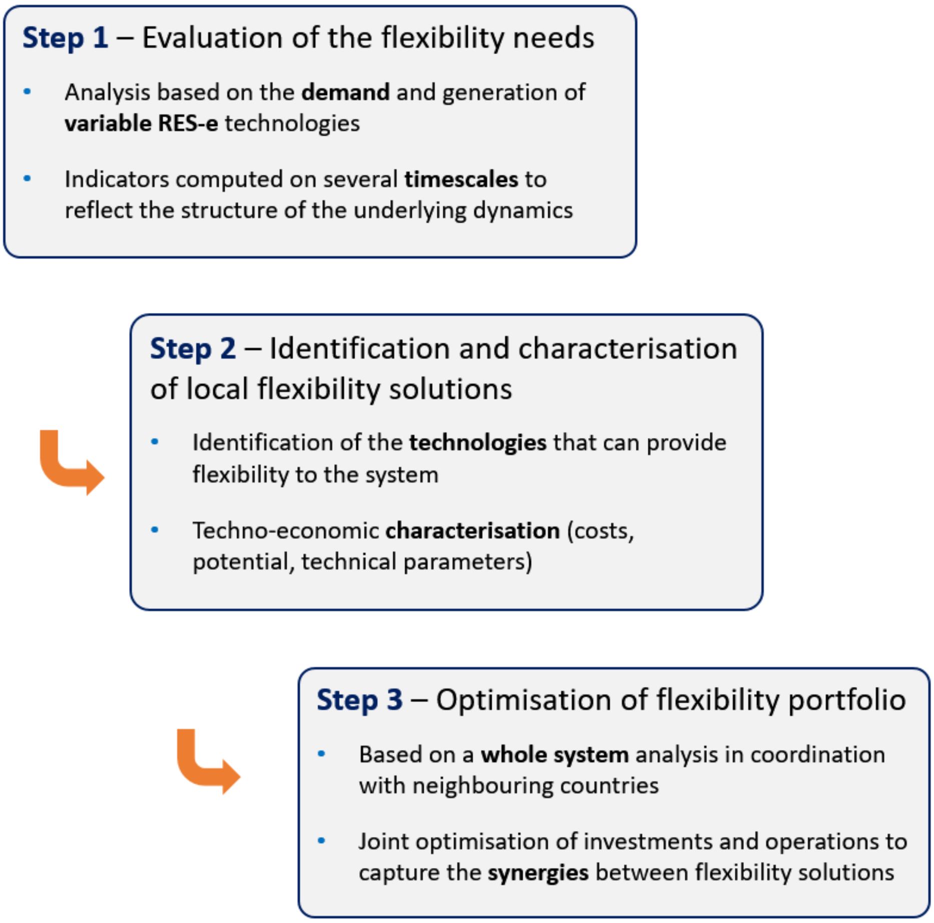

Figure 1 - Recommended framework to establish flexibility portfolios

Step 1 - The first step aims at evaluating the flexibility needs on at least three different timescales: daily, weekly and annual assessments are recommended in order to capture the following phenomena:

- Daily flexibility needs are found to be mostly driven by the share of solar power and by the dynamics of the demand (the deployment of electric vehicles, residential consumption habits, the structure of the economy, etc. influence the occurrence and importance of demand peaks). In particular, it is shown in this report that solar power can reduce the daily flexibility needs at first, but that when its deployment exceeds a country-specific threshold, the integration of solar power results in higher flexibility needs.

- Weekly flexibility needs are shown to be mostly driven by the share of wind power (at the national scale, wind regimes have a typical duration of the order of a few days) and of the weekday/weekend pattern of the demand.

- Annual flexibility needs are found to be mostly driven by the electrification of heat, the share of solar power and the share of wind power. In most countries, the electricity demand is higher during wintertime than during summertime due to heating. This means that, generally speaking, wind power, which tends to produce more during wintertime than during summertime, reduces the need for annual flexibility, while the deployment of solar power, which has the opposite annual generation pattern, results in higher annual flexibility needs.

Step 2 - The aim of the second step is to identify and characterise the flexibility solutions that are locally available. A balanced portfolio of flexibility solutions is found to be beneficial in terms of investment and operational costs. One should therefore take into account all the resources that can provide flexibility: flexible generation, the retrofit of existing power plants, storage units with different discharge times (batteries, compressed air, pumped-hydro, flywheels, etc.), demand-response with different characteristics (industrial, commercial, residential, etc.), system-friendly RES-e technologies (e.g. east-west solar units, concentrated solar power with storage, advanced wind turbines, etc.) and interconnectors. The costs, potentials and techno-economic characteristics of each of the flexibility solutions are collected during this step.

Step 3 - Finally, a whole system analysis is recommended when establishing the optimal contribution of each of the flexibility solutions in the provision of flexibility. The time resolution of the modelling tool should be at least hourly, in order to capture the ramping challenges related to the deployment of solar power (the well-known duck-shape challenge), while the modelling horizon should at least be of one entire year so as to be able to describe the integration challenges on all timescales: at the daily, weekly and annual levels. Using several weather scenarios can be valuable in order to properly take into account the variability of the climate from one year to the other. When performing the assessment at the Member State level, it is recommended that neighbouring be explicitly represented in the model, in particular not to overestimate the level of required investments when performing adequacy assessments. Member States should be encouraged to share assumptions and methodologies to ensure their respective NECPs are compatible with one another and exploit potential regional synergies.

Application of the recommended methodology

The above framework has been applied to the METIS EUCO30 scenario for the year 2030. Three options have been considered in order to highlight the potential roles of the different flexibility solutions. As indicated by Table 1, the RES-e, nuclear, coal, lignite, and waste capacities are the same in all three options. The set of flexibility solutions in which the model can invest differ between the options and are presented in the two first lines of Table 1.

		Option (I)	Option (II)	Option (III)
Optimised deployment	Available flexibility solutions	Gas-fired generation	Gas-fired generation **Demand-response** **Storage**	Gas-fired generation **Demand-response** **Storage** **Interconnectors**
	Available flexibility improvements	Coal retrofits Gas retrofits	Coal retrofits Gas retrofits **Advanced onshore wind**	Coal retrofits Gas retrofits **Advanced onshore wind**
Assumptions	Based on METIS EUCO30	Solar, wind, run-of-the-river, large hydro, biomass, waste, nuclear, coal and lignite capacities, fuel and CO_2 prices, annual demand		
	Other assumptions	Interconnectors (current network + currently under construction) Storage technologies (2015 capacities) Demand-response (2015 capacities)	Interconnectors (current network + currently under construction)	

Table 1 - Definition of the options

In Option (I), the model is only allowed to invest in thermal capacities: either through investments in additional gas-fired capacities (OCGTs and CCGTs), or by retrofitting existing coal and gas plants. In Option (II), investments in demand-response, storage and advanced wind turbines are made available to the model, and, finally, in Option (III), the model is given the possibility to increase some of the interconnection capacities, based on the latest list of Projects of Common Interest.

The main findings are summarised below:

- <u>There is an important dispersion of the flexibility needs among Member States</u>
  The flexibility needs of all Member States have been evaluated on three different timescales so as to take all the underlying phenomena into account: daily solar cycle, wind regimes, the difference in consumption between weekdays and weekends, the annual variation of solar and wind power (solar generation is higher during summertime, while wind generation tends to be higher during wintertime), and the annual variation of consumption (either due to heating or to air conditioning). Flexibility needs therefore strongly depend on the ambition in terms of RES-e deployment, but also on other characteristics of the local

energy system: structure of the economy, presence of electric heating or air conditioning, etc.

- A diversified portfolio of flexibility solutions generates important benefits
  Overall, investing in a diversified portfolio of flexibility solutions results in annual benefits of 1.9 B€ in Option (II) at the EU28 level compared to Option (I), and of 2.8 B€ in Option (III) compared to Option (I). The benefits mainly originate from a better exploitation of RES-e technologies, baseload and mid-merit resources that is enabled by investments in demand-response, storage and interconnectors. These additional investments in Options (II) and (III) decrease the need for gas-fired generation and are found to generate annual investment savings of the order 150 M€ and 210 M€ respectively at the EU28 level by replacing 15 and 25 GW respectively of gas-fired capacity by other flexibility solutions. As a result of these investments, when comparing the performance of the electricity systems in each of the three options, the systems of Options (II) and (III) are found to be considerably less expensive to operate: the ability to use demand-response, storage and interconnectors to better exploit RES-e, baseload and mid-merit resources reduces the number of occurrences when peaking plants with high variable and start-up costs have to be run. Operational costs can be reduced by around 1.2 B€ per year in Option (II) compared to Option (I), and a further 700 M€ can be saved in Option (III). These results are summarised in Table 2.

Indicator [M€/year]	Option (I)	Option (II)	Option (III)
Investment costs[1]	8 180	8 030	7 970
Investment savings	-	150	210
Production costs	71 200	70 000	69 300
Production savings	-	1 200	1 900
Welfare gains	-	1 800	2 600
Total benefits (investment savings and welfare gains)	-	1 950	2 810

Table 2 - Summary of the impacts on costs and welfare at the EU28 level

The increase of social welfare is found to be more important than the production savings due to the decrease of loss of load episodes in Options (II) and (III), and a geographical distribution of welfare between the EU and to other modelled countries that is favourable to the EU.

[1] One should note that the investment costs strongly depend on the assumed level of residual capacities in the gas sector (i.e. the currently existing gas-fired generation units that are assumed to remain operational in 2030).

- There is no "one-size-fits-all" solution to the flexibility challenge
  The results of the modelling exercise carried out for this report show that there is no "one-size-fits-all" solution to the flexibility challenge. Indeed, just as flexibility needs are found to exhibit significant differences between Member States, the optimal portfolio of flexibility solutions depends on a number of local and regional factors: deployment of variable RES-e technologies, availability of sites for pumped-hydro storage and compressed-air storage, structure of the industrial sector and ability to participate in demand-response programmes, level of interconnection with neighbouring countries, costs of flexibility solutions, etc. This advocates carrying out dedicated assessments at Member State level such as the one presented herein, taking into account local specificities and potential synergies with neighbouring countries, and being conscious of the limitations of generic approaches.

- General lessons can be drawn from the European portfolio of flexibility solutions
  Despite the fact that the national optimal portfolios of flexibility solutions strongly depend on the local circumstances, the following lessons can be drawn at the European level:
  - Allowing storage, demand-response, system-friendly RES-e technologies and interconnectors to participate in the provision of flexibility results in substantial savings in terms of investments, and, most importantly, in terms of operational costs.
  - Investments in industrial load-shedding, domestic load-shifting, storage technologies and interconnectors allow for a better use of cheap resources (baseload and mid-merit units) by reallocating demand across time (demand-response and storage) and countries (interconnectors).
  - Demand-response and batteries are found to advantageously replace conventional generation (thermal and hydro power plants) for the provision of reserves in a vast majority of Member States. As a consequence, baseload and mid-merit technologies are able to increase their electricity generation and thereby to avoid the opportunity cost related to the provision of reserves.
  - Along to thermal units, hydropower and interconnectors are found to be providing the bulk of the required daily and weekly flexibility at the European level.
  - System-friendly wind turbines are found to substantially decrease the weekly flexibility needs thanks to the lower level of fluctuation of their generation profiles.

Through the modelling exercise presented in this report we demonstrate that flexibility solutions such as demand-response, storage, interconnectors, retrofit of thermal units and system-friendly RES-e technologies are essential ingredients to improve the cost-effectiveness of the European power sector.

Main limitations of the modelling exercise

The quantitative analysis presented in this study is based on modelling which relies on a number of assumptions in terms of inputs. We do not expect the conclusions drawn above to be significantly impacted by the limitations, but recommend that Member

States take the following considerations into account, should they wish to replicate the exercise:

- The 2030 PRIMES EUCO30 RES-e capacities and capacity factors are adopted for this study. It is recommended that Member States replicate a similar exercise using their own projected RES-e capacity deployment towards 2030, as foreseen in their NECPs.
- It should be noted that the determination of the optimal portfolios of flexibility solutions depends on a number of input data (e.g. costs and potential for flexibility solutions at the Member State level). In particular, the investments in further interconnection capacity considered in this study are based on the latest list of Projects of Common Interest, which derive from different sets of assumptions and considerations. The study also uses the same discount rate for all investments – in reality, the cost of capital and the rates of return expected by investors can considerably vary among technologies and Member States. The results should therefore not be interpreted as the optimal set of investments.
- Given the important role demand-response can have in the provision of reserves and of flexibility, taking into account the potential associated with specific uses, or appliances, is recommended. In this study, the demand-response potentials that are considered are related to industrial load shedding and reserve supply by storage-related demand-response (electric vehicles, domestic hot water, heating and cooling).
- This study focuses on generation adequacy at the national level. The ability of flexibility solutions to avoid or defer investments in internal transmission network and distribution network reinforcements should ideally also be taken into account.
- The optimisation carried out in this study aims at maximising the European social welfare. Since several Member States can benefit from the investments in large-scale projects such as pumped-hydro storage or interconnectors, one can imagine that the costs could also be distributed among Member States. This study does not consider the cross-border re-allocation of costs and benefits.
- The carbon price has been held constant in all options, regardless of the amount of CO_2 emissions. It should be noted that this assumption is not consistent with the increase in CO_2 emissions observed in the modelling exercise in Option (II) and Option (III), which is due to the higher electricity production of coal and lignite units. This increase in CO_2 emissions should in turn lead to an increase in the EU-ETS price, making coal and lignite units less economic to operate. In the end, these interactions would lead to a new equilibrium in the CO_2 market, where the EU-ETS price is higher, but overall emissions at EU28 level are roughly the same. However, the increase of the CO_2 price that would be necessary to reduce CO_2 emissions to their Option (I) level would not be large enough to trigger a coal-to-gas switching in the merit order, and would consequently have a limited impact on the results presented herein.

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1 Introduction

The Energy Union Strategy

The Energy Union strategy[2] is the European framework that was introduced in 2015, prior to the Paris Conference of Parties to the UNFCCC (COP21), to ensure that Europe can meet its ambitious energy and climate objectives. It is within this framework that the EU defines the policies and legislative measures allowing it to fulfil the pledge contained in its Intended Nationally Determined Contribution (INDC), which states that "*the EU and its Member States are committed to a binding target of an at least 40% domestic reduction in greenhouse gas emissions by 2030 compared to 1990*"[3].

The Energy Union strategy sets out a holistic approach, aiming at creating a new momentum to bring about the transition to a low-carbon, secure and competitive economy that is compatible with the EU COP21 pledge under the 2015 Paris Agreement[4].

Pursuing the decarbonisation of the European power sector, while, at the same time, improving the security of supply, and increasing competitiveness, contributes to the effort towards meeting the EU's decarbonisation objectives[5]. In 2014, the carbon intensity of the electricity generation at the EU28 level was around 280 gCO_2/kWh[6]. Even if progress has been made during the 1990-2014 period (-36% in terms of carbon intensity) thanks to the increased production efficiency and the transition from fossil fuels to renewables, the European electricity generation sector still has room for improvement. Indeed, electricity generation based on fossil fuels accounts for around 49% of the 2016 total net production of electricity in EU28[7]. It is by combining efforts in the field of energy efficiency and carbon intensity that the EU will progressively decarbonise its electricity sector.

Furthermore, in order to achieve the decarbonisation of the power sector, and of the economy in general, the Energy Union strategy recognises the crucial role of solidarity and cooperation between Member States, and of the integration of their internal energy markets.

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[2] COM(2015) 80 final – A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy

[3] http://www4.unfccc.int/Submissions/INDC/Published%20Documents/Latvia/1/LV-03-06-EU%20INDC.pdf

[4] http://unfccc.int/paris_agreement/items/9485.php

[5] In 2014, the supply of electricity, gas, steam and air conditioning was responsible for 26% of the European CO_2eq emissions. Source: Eurostat (online data code: env_ac_ainah_r2)

[6] National emissions reported to the UNFCCC and to the EU Greenhouse Gas Monitoring Mechanism, European Environment Agency

[7] Eurostat (online data code: nrg_105a, nrg_105m)

The role of renewables in the context of the 2030 energy and climate objectives

The 2030 energy and climate objectives, in line with the Paris agreement pledge and the 2050 Energy Strategy[8], include at least 27% renewable energy consumption. It can be estimated that this target translates into a share of around 50% of renewable energy in the electricity sector[9] in 2030, compared to a share of 28.8% in 2015[10].

After a decade of rapid growth, renewable electricity sources have grown to become an essential part of the European electricity supply. At the early stages of their deployment, the challenges related to the integration of variable RES-e technologies were similar to those arising when having to adapt to an uncertain demand. However, this situation has already considerably changed in a number of Member States, and will likely continue to evolve:

- The competitiveness of RES-e technologies will likely continue to grow at a steady pace in the years to come. Variable RES-e technologies already constitute the bulk of the investments in the RES-e sector, thanks to the continued price decline of both solar and wind technologies. Other less established variable technologies such as tidal or wave sources may also see their market penetration increase, provided their costs continue to decrease. The share of electricity generated by variable RES-e technologies has risen considerably over the past years, and one can expect this tendency to continue, if not accelerate, in the next years and decades.

- Carbon-intensive generating units and other thermal fleets progressively have to be replaced. This is either driven by policy decisions (e.g. coal phase-out in the UK, nuclear phase-out in Germany), or by the fact that these units have reached the end of their safe operational lifetimes.

The period between 2020 and 2030 will be an opportunity to rethink the way the European power systems are designed by not limiting oneself to adapting the power systems to renewables, but by placing renewables and their specificities at the core of the design of the European power system.

Challenges related to the integration of variables RES-e sources

As a consequence of the variable nature of the power generation pattern of RES-e technologies such as PV and wind, and of the difficulty to forecast these patterns, the very way one designs and operates electricity systems has to evolve.

First, the variability of the power generation patterns (daily cycles for solar generation, wind regimes, etc.) calls for a more flexible and responsive power system. Indeed, the dispatchable technologies have to continuously adapt their operations to the quantity of electricity generated by variable RES-e technologies (on the condition the market design

[8] COM(2011) 885 final – Energy Roadmap 2050.

[9] https://ec.europa.eu/energy/sites/ener/files/documents/technical_memo_renewables.pdf

[10] Eurostat (online data code: tsdcc330)

provides the appropriate set of incentives). For example, the higher the share of PV, the steeper the ramps of the residual load are (i.e. the load that has to be met by the other market participants such as conventional generating units, storage units, demand-side management, etc.). The penetration of wind turbines also requires flexibility capacity of the power system to be dimensioned accordingly, especially on the weekly timescale since wind regimes are found to vary with a period of a few days at the national level. Moreover, as the generation and demand patterns can substantially vary across Member States, electricity interconnectors play an essential role in the provision of flexibility by allowing electricity to dynamically flow across borders from places where RES-e generation is abundant and would potentially have to be curtailed to places where costs related to starting and running conventional thermal generation units can be avoided. A cost-effective management of the power system therefore not only relies on the portfolio of available technologies, but also on the market design: ensuring that all technologies compete on a level playing field and that the short-term markets are well integrated across Europe are essential ingredients of a successful response to the flexibility challenge.

Second, the traditional way system adequacy is addressed is challenged in the presence of a large share of variable RES-e technologies. Indeed, even if at some times the power output of solar or wind technologies can be negligible in a given Member State, this does not mean that one should plan to build local thermal backup capacities to ensure the demand can be met by the local system during such episodes. The system adequacy should rather be addressed at a regional or EU level, by taking into account that the generation patterns of variable RES-e technologies and of the demand vary considerably between Member States, allowing them to share the excess of RES-e production with neighbours. In particular, the amount of backup capacity (conventional generation, storage, demand-response, etc.) that should be introduced in the power system should be assessed at the regional or EU-level in order to avoid massive overinvestments in peaking units[11].

[11] Artelys, *METIS Study S04 – Generation and System Adequacy Analysis*, 2016

The Clean Energy for All Europeans package

On November 30th, 2016, the European Commission has taken steps to consolidate the enabling environment for the transition to a low carbon economy. The Clean Energy for All Europeans package of legislative proposals[12] covers energy efficiency, renewable energy, the design of the electricity market, security of electricity supply, and governance rules for the Energy Union.

The Commission has largely emphasised the benefits of regional cooperation in a number of sectors (system adequacy assessment, reserve dimensioning, competition between balancing service providers, RES-e tendering procedures, etc.), and the importance of defining a level playing field for all technologies (e.g. by allowing demand-response and variable RES-e technologies to participate in the procurement of balancing reserves, or by ensuring all technologies are subject to the same balancing responsibilities).

A fair competition among technologies and regional cooperation will play key roles in ensuring that variable RES-e technologies are integrated in a cost-efficient way and are at the core of the present report. Indeed, regional cooperation has been shown to reduce the need for investments, while competition among technologies allows the system to diversify the portfolio of flexible solutions that have to be introduced to address the flexibility challenge.

The Energy Union governance proposal: National Energy and Climate Plans

The Energy Union governance proposal included in the Clean Energy for all Europeans package aims at ensuring that national policies and objectives are in line with EU goals. According to the proposed governance rules, Member States will be required to develop Integrated National Energy and Climate Plans (NECPs) that cover the five dimensions of the Energy Union for the period 2021 to 2030 (and every subsequent ten year period) and to report on the progress they make in implementing these NECPs.

In particular, Article 4 of COM(2016) 759 final/2 states that Member States should set "*national objectives with regard to ensuring electricity system adequacy as well as flexibility of the energy system with regard to renewable energy production, including a timeframe for when the objectives should be met*", while Article 21 requires that Members States report information on the "*measures to increase the flexibility of the energy system with regard to renewable energy production, including the roll-out of intraday market coupling and cross border balancing markets*".

[12] COM(2016) 860 final

Objectives of this report

The objectives of this report are to provide assistance to Member States by setting out a framework which can be used to compose optimal portfolios of flexibility solutions that lead to a cost-effective integration of variable RES-e technologies. The report also provides Member States with references to a number of publicly available datasets and publications that can be exploited when carrying out such exercises. Finally, the recommended methodology is applied at the European level by optimising the portfolio of flexibility solutions to meet the flexibility needs arising in the METIS EUCO30 scenario.

The methodology is applied using the METIS model, which has been developed by Artelys for the European Commission, with the support of IAEW (RWTH Aachen University), Frontier Economics, and ConGas, and exploits the capacity expansion planning capabilities of the Artelys Crystal Super Grid software.

Structure of the document

The remainder of the document is organised as follows:

- Section 2 sets out the recommended methodology to define flexibility portfolios
- Section 3 applies the methodology at the European level
- Section 4 presents our conclusions
- Annex A presents the models that have been used in this study
- Annex B contains the detailed results of the methodology applied in Section 3 for each Member State

2 Recommended methodology to define flexibility portfolios

2.1 Overview

This section sets out the recommended methodology to define flexibility roadmaps. As described in the introduction to this report, a cost-effective integration of a large share of variable RES-e technologies relies on the ability of the power system to provide flexibility. A fixed RES-e installed capacity can have very different impacts on the power system depending on the composition of the flexibility portfolio: under appropriate market conditions, storage and demand-response can help shifting the RES-e power output across timeframes, while interconnectors can allow Member States to share resources across borders.

This section first presents the recommended methodology to evaluate and characterise the flexibility that is required in power systems with high shares of variable RES-e technologies. After the identification and characterisation of the potential sources of flexibility, we then proceed to the presentation of the way these solutions can be combined to meet the identified flexibility needs.

The methodology that we recommend is based on three steps:

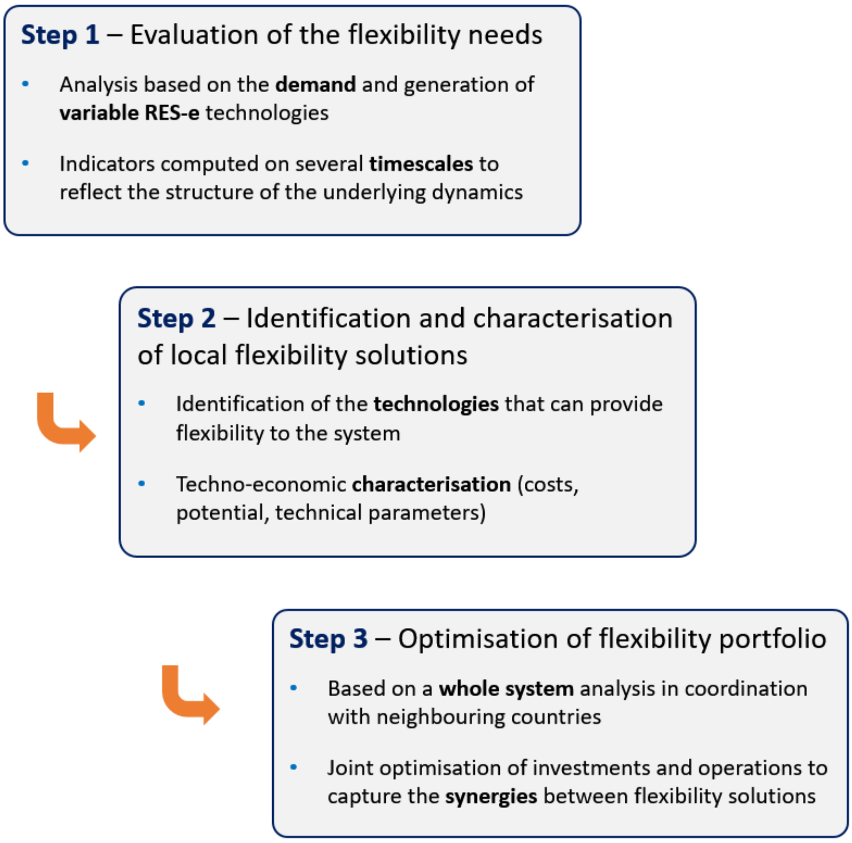

Figure 2 - Recommended framework to establish flexibility portfolios

Compared to a traditional approach where one would only rely on conventional generation to provide the flexibility required to ensure a given security of supply criterion is met, a balanced flexibility portfolio that includes demand-response, storage and interconnectors, will be shown in Section 3 to result in lower investment and operational costs.

Section 3 of this report contains an application of the methodology at the European level (the Member State level results are shown in Annex B). Therefore, for each of the three steps introduced above, we include a general description of the recommended process, a list of publicly available resources that can be exploited to perform the corresponding computations, and we describe the way we applied the methodology to produce the results presented in Section 3.

2.2 Step 1 - Evaluation of flexibility needs

2.2.1 Methodology

The first step of the methodology is to define how flexible the system needs to become in the presence of a large share of RES-e sources in order to cope with variations in demand and/or in generation. Several effects influence the flexibility needs on different timeframes:

- At the hourly and sub-hourly levels, the increase of flexibility needs are mostly driven by the required ability to face the imbalances caused by RES-e forecasting errors.

- At the daily level, the flexibility needs are found to be mostly driven by the daily pattern of the demand and by the daily cycle of solar generation.

- At the weekly level, the flexibility needs are mostly driven by wind regimes and by the weekday/weekend demand structure.

- Finally, at the annual level, the flexibility needs are mostly driven by a combination of the solar, wind and demand patterns. The solar production is higher during summertime, while wind generation tends to have an opposite behaviour. The last factor influencing the annual flexibility needs is the load-temperature sensitivity, which can be very contrasting from one Member State to the other depending on the portfolio of heating and cooling technologies.

In the following we define daily, weekly and annual flexibility needs by analysing the dynamics of the residual load on several timescales, so as to take into account all the underlying phenomena that drive the need for flexibility.

Definition – Residual load

The residual load is defined as the load that has to be served by dispatchable technologies (thermal, hydro, storage, demand-response, interconnectors, etc.). It is computed by subtracting the wind, solar and must-run generation from the demand. In order to capture the flexibility needs that are required to perform the analysis recommended in this report, we advise to use an hourly time resolution.
The residual load is illustrated below for a given week. The solid red line represents the demand, the solid blue line the residual load, while the green and yellow areas represent the wind and solar generation.

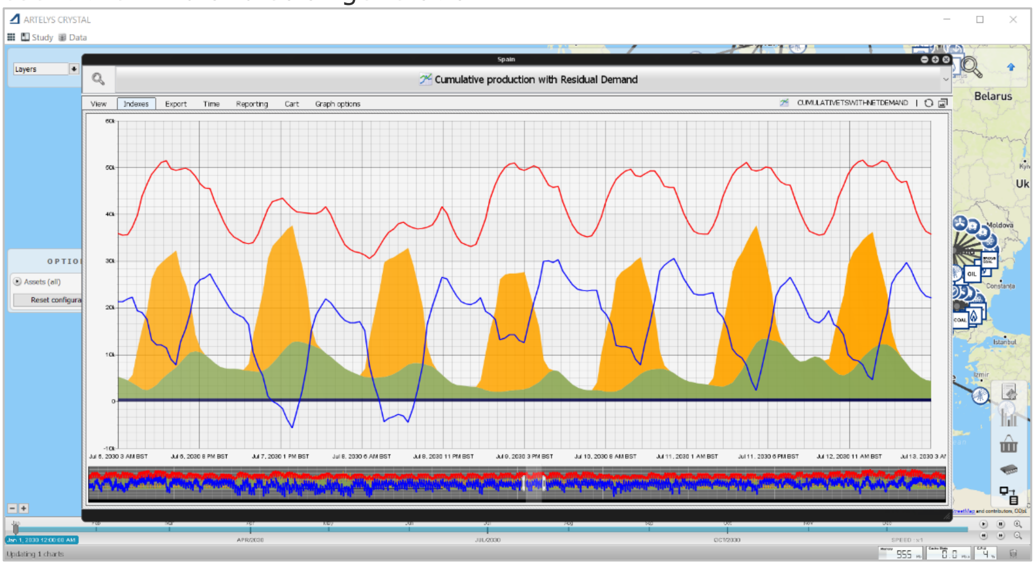

Figure 3 - Residual load illustration in Artelys Crystal Super Grid

Flexibility is defined as the ability of the power system to cope with the variability of the residual load curve at all times. Hence, flexibility needs can be characterised by analysing the residual load curve.

Daily flexibility needs

On a daily basis, if the residual load were to be flat, no flexibility would be required from the dispatchable units. Indeed, in such a situation, the residual demand could be met by baseload units with a constant power output during the whole day. In other words, a flat residual load does not require any flexibility to be provided by dispatchable technologies.

We therefore define the daily flexibility needs of a given day by measuring by how much the residual load differs from a flat residual load. The daily flexibility needs computed in this report are obtained by applying the following procedure:

1. Compute the residual load over the whole year by subtracting variable RES-e generation and must-run generation from the demand
2. Compute the daily average of the residual load (365 values per year)

3. For each day of the year, compute the difference between the residual load and its daily average (the light green area shown on Figure 4). The result is expressed as a volume of energy per day (TWh per day).
4. Sum the result obtained over 365 days. The result is expressed as a volume of energy per year (TWh per year).

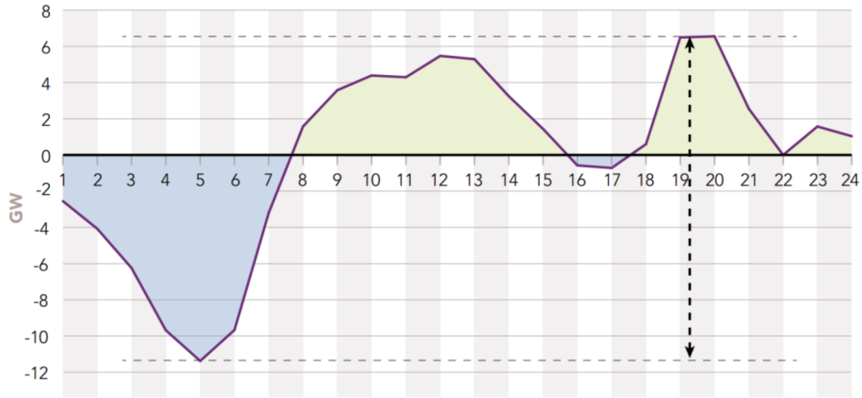

Figure 4 - Illustration of daily flexibility needs (the solid purple line measures the deviation of the residual load from its daily average for a given day). Source: RTE, Bilan prévisionnel de l'équilibre offre-demande, 2015

Weekly flexibility needs

The same reasoning is applied to evaluate the weekly flexibility needs. However, in order not to re-capture the daily phenomena that are already taken into account by the daily flexibility needs indicator, we recommend adopting the following procedure:

1. Compute the residual load over the whole year by subtracting variable RES-e generation and must-run generation from the demand with a daily resolution
2. Compute the weekly average of the residual load (52 values per year)
3. For each week of the year, compute the difference between the residual load (with a daily resolution) and its weekly average (the light green area shown on Figure 5). The result is expressed as a volume of energy per week (TWh per week).
4. Sum the result obtained over 52 weeks. The result is expressed as a volume of energy per year (TWh per year).

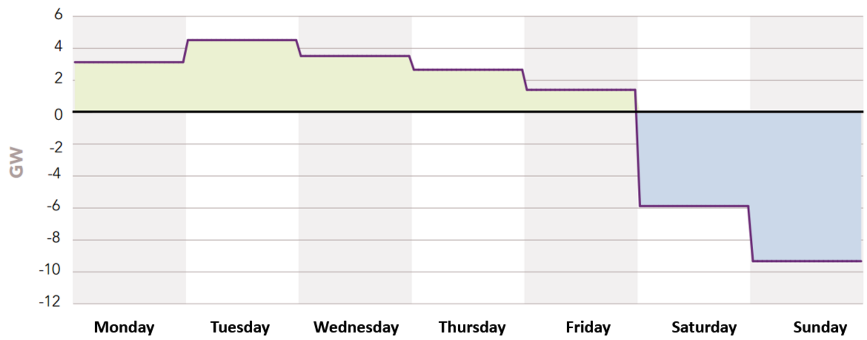

Figure 5 - Illustration of daily flexibility needs (the solid purple line measure the deviation of the residual load from its daily average for a given week). Source: RTE, Bilan prévisionnel de l'équilibre offre-demande, 2015

Annual flexibility needs

Finally, the annual flexibility needs are assessed in a similar way:

1. Compute the residual load over the whole year by subtracting variable RES-e generation and must-run generation from the demand with a monthly time resolution
2. Compute the annual average of the residual load
3. Compute the difference between the residual load (with a monthly time resolution) and its annual average. The result is expressed as a volume of energy per year (TWh per year).

Alternative metrics

Alternative metrics can be introduced to evaluate flexibility needs:

- Instead of using the difference between the residual load and its average (as for the three indicators introduced above), one can assess the flexibility capacity requirements by computing the difference between the maximum and the minimum values of the residual load (see dashed arrow on Figure 4).
- The average hourly ramping rate per hour of the day can provide an assessment of the additional flexibility that is required from the power system when the deployment of RES-e technologies increases. Figure 6 shows the impact of a further deployment of RES-e on the average hourly ramping rates.

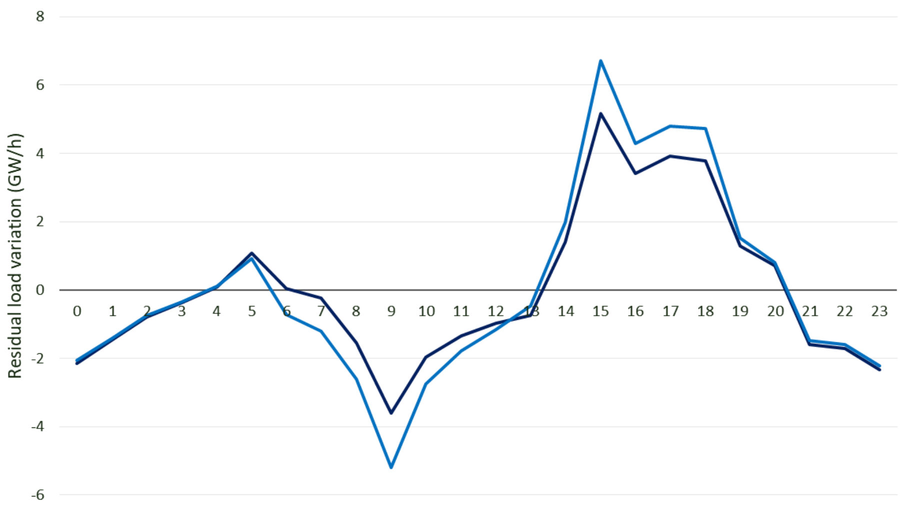

Figure 6 – Illustration of the residual load variation in two scenarios with different RES-e shares. The light blue scenario (high RES share) requires more ramping than the dark blue scenario (low RES share)

In particular, the following indicators can be useful: maximum ramping rate (in GW/h), histograms of ramping rates (to estimate the number of hours during which a given ramping rate is required).

- Finally, analyses based on the residual load duration curve can be helpful, even though the dynamics of the flexibility needs is lost in such assessments.

For more alternative flexibility metrics, we refer the reader to the "Mainstreaming RES - Task 3.1: Historical assessment of progress made since 2005 in integration of renewable electricity in Europe and first-tier indicators for flexibility" report.

2.2.2 Publicly available data sources

The computation of the daily, weekly and annual flexibility needs for a given year and a given Member State requires demand time-series, and solar and wind generation time-series, with an hourly time resolution. The next paragraphs describe some of the main sources of publicly available datasets.

Demand time-series

For most Member-States, the current demand time-series are available on ENTSO-E's Transparency Platform[13]. However, both the volume and profile of the demand can be expected to evolve by 2020, 2025 or 2030 due to energy efficiency efforts, electrification of the heat and mobility sectors, population growth, economic growth, etc.

A number of prospective scenarios are publicly available, although most of them do not provide hourly time-series:

- PRIMES Reference Scenario 2016 and EUCO scenarios
  PRIMES is a partial-equilibrium model of the energy system. It has been used extensively by the European Commission for setting the EU 2020 targets, the Low Carbon Economy and the Energy 2050 Roadmaps, as well as the 2030 policy framework for climate and energy. A number of scenarios, based on different policy assumptions, are available on the Commission's website. While the PRIMES Reference Scenario 2016 is a scenario based on the current policy framework, the EUCO scenarios are policy scenarios based on different ambition levels (in particular in terms of energy efficiency and share of renewables). The EUCO27 and EUCO30 scenario comply with all the 2030 climate and energy targets as agreed by the European Council in 2014[14] (the first one with a 27% energy efficiency target, and the second one with a 30% energy efficiency target).

  Link: https://ec.europa.eu/energy/en/data-analysis/energy-modelling

- ENTSO-E TYNDP 2016
  Every second year, ENTSO-E publishes its ten-year network development plan (TYNDP). The latest edition, TYNDP 2016, includes a 2020 scenario ("Expected Progress") and four 2030 visions, which are contrasting but possible futures of the European power system. The visions differ in terms of annual demand, demand patterns, installed capacities, and fuel and CO_2 prices. The 2018 version of the TYNDP, which is not available at the time of writing, should also include a number of 2040 scenarios.

  Link: http://tyndp.entsoe.eu

[13] https://transparency.entsoe.eu, Actual Total Load

[14] European Council conclusions, 23/24 October 2014

The following table summarises the availability of the main publicly available demand-related datasets.

Source	Annual demand volume at Member State level	Hourly time-series at Member State level
PRIMES Reference Scenario 2016	Yes, between 2000 and 2050, by steps of 5 years	No
PRIMES EUCO scenarios	Yes, between 2000 and 2030, by steps of 5 years	No
ENTSO-E TYNDP 2016	Yes, one 2020 scenario and 4 contrasting visions for 2030	Yes

Table 3 - Publicly available demand scenarios

At the time of writing, the only publicly available time-series for prospective scenarios that the authors are aware of are the ENTSO-E TYNDP 2016 time-series. These time-series can easily be rescaled so that the resulting annual demand corresponds to the annual demand of another scenario. We recommend choosing with care which of the time-series to use, as there are notable differences between the ENTSO-E's visions, in particular in terms of demand-response, which influence the dynamics of the demand.

The application of the methodology recommended in this report, which can be found in Section 3, is based on the demand time-series of the METIS EUCO30 scenario[15]. The METIS EUCO30 time-series were built by rescaling the ENTSO-E TYNDP 2014 Vision 1 time-series so that the annual demands at Member State level correspond to the ones of the PRIMES EUCO30 scenario. Finally, 50 years of power demand time-series have been generated, based on historical temperature data and national thermal gradients (load-temperature sensitivity).

Solar and wind generation time-series

The datasets that are required to characterise solar and wind generation are similar in nature to the ones needed for the demand: both the annual volume of solar and wind production, and the generation time-series enter the computation.

All the PRIMES and ENTSO-E scenarios listed above provide annual solar and wind production figures, but none of them includes hourly generation time-series.

Thankfully, the European Commission's Joint Research Centre (JRC), in an effort to promote transparent and reproducible energy modelling, has recently published the two first EMHIRES datasets[16]:

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[15] The demand data as well as the PV and wind generation time-series of METIS will be published on the DG ENER webpage dedicated to METIS (http://ec.europa.eu/energy/en/data-analysis/energy-modelling/metis).

[16] GONZALEZ APARICIO Iratxe; ZUCKER Andreas; CARERI Francesco; MONFORTI Fabio; HULD Thomas; BADGER Jake; EMHIRES dataset. Part I: Wind power generation European Meteorological derived HIgh resolution RES generation time series for present and future scenarios; EUR 28171 EN; 10.2790/831549.; GONZALEZ APARICIO Iratxe; MONFORTI Fabio; VOLKER Patrick; ZUCKER Andreas; CARERI Francesco; HULD Thomas; BADGER Jake. Simulating European wind power generation applying statistical downscaling to reanalysis data. Applied Energy

- EMHIRES Dataset Part I – Wind power generation
  Description: this dataset contains 30 years of hourly wind power capacity factors at country level (onshore and offshore), as well as at bidding zone, NUTS1 and NUTS2 levels. These datasets correspond to the capacity factors the 2015 wind fleet would have reached in the wind conditions of 1986 to 2015.

  Link: https://setis.ec.europa.eu/related-jrc-activities/jrc-setis-reports/emhires-dataset-part-i-wind-power-generation

- EMHIRES Dataset Part II – Solar power generation
  Description: this dataset contains 30 years of hourly PV power capacity factors at country level, as well as at bidding zone, NUTS1 and NUTS2 levels. These datasets correspond to the capacity factors the 2015 solar fleet would have reached in the irradiance conditions of 1986 to 2015.

  Link: https://setis.ec.europa.eu/related-jrc-activities/jrc-setis-reports/emhires-dataset-part-ii-solar-power-generation

The application of the methodology recommended in this report, which can be found in Section 3, is based on the PV and wind energy generation time-series of the METIS EUCO30 scenario. These time-series have been built by IAEW-RWTH Aachen University, and, unlike the EMHIRES datasets, take into account a certain amount of technological progress of the solar and wind fleets by 2030.

(2017) 199, 155-168; GONZALEZ-APARICIO Iratxe, HULD Thomas, CARERI Francesco, MONFORTI Fabio, ZUCKER Andreas; EMHIRES dataset - Part II: Solar power generation. European Meteorological derived HIgh resolution RES generation time series for present and future scenarios. Part II: PV generation using the PVGIS model; EUR 28629 EN; doi: 10.2760/044693

2.3 Step 2 - Identification and characterisation of the local flexibility solutions

2.3.1 Methodology

The objective of the second step of the recommended methodology is to establish the list of flexibility solutions that should be considered to provide the flexibility required by the integration of large shares of RES-e technologies, and to characterise these solutions.

As will become clear in Section 3, there is no "one-size-fits-all" solution to the flexibility challenge. The optimal portfolio of flexibility solutions at Member State level depends on the one hand on the flexibility needs (*Step 1*) and on the other hand on locally available flexibility solutions (*Step 2*). Indeed, the potential and costs of most of the flexibility solutions (pumped-hydro storage (PHS), compressed air energy storage (CAES), demand-response, interconnectors) can substantially vary among Member States, and depend on the availability of sites (PHS, CAES), the composition of the industrial sector (industrial demand-response), the geographical situation in Europe and the route that interconnectors would follow (subsea, land topography, etc.).

In the following paragraphs, we qualitatively describe the set of flexibility solutions that should be considered, and list the techno-economic characteristics that have to be collected so as to be able to determine their potential role in the provision of flexibility.

Flexible generation technologies

The flexible generation technologies are the conventional sources of flexibility: thermal assets such as open-cycle gas turbines (OCGTs), combined-cycle gas turbines (CCGTs), reciprocating engines, and hydro units. In function of their ability to ramp up or down, and of their cycling costs, these flexibility solutions can adapt to the variable nature of the solar and wind power outputs. However, heavily relying on conventional thermal sources of flexibility is in most cases associated with high production costs, as will be illustrated in Section 3.

The role of flexible generation technologies is not limited to the integration of variable renewables, as they can provide additional services to the grid such as frequency and voltage control, black start, etc. These additional revenue streams can mitigate the financial risks faced by peaking plants if they are not able to capture sufficient market revenues[17].

Retrofitting existing flexible thermal units is one of the measures some countries have taken in order to increase the provision of flexibility by conventional units. Retrofitted units can benefit from an increased efficiency, an ability to ramp up and down more quickly and the ability to have a lower minimum stable generation level.[18]

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[17] See Artelys, *METIS Study S16 – Weather-driver revenue uncertainty and ways to mitigate it*, 2016.

[18] See for instance Agora Energiewende, "*The Danish Experience with Integrating Variable Renewable Energy*", 2015.

List of techno-economic parameters

- Investment costs (in k€/MW)
- Operation and maintenance costs (in k€/MW/year)
- Fuel costs (in €/therm, €/tonne, €/bbl, etc.)
- Starting costs (in €/MW)
- CO_2 intensity (in tonne/MWh)
- Efficiency (in %)
- Technical constraints: minimum stable generation, ramping rates, minimum off-time, availability
- Potentially, environmental constraints

Storage

Storage is a very versatile technology that can provide a wide range of applications. As a flexibility solution, it can store excess energy for later use. Depending on the discharge time of the considered storage technology (energy to capacity ratio), a given unit can provide sub-hourly regulation services and/or arbitrage services (e.g. by storing the excess PV and feeding it back into the grid during evening peak demand episodes).

Next to regulation and arbitrage services, storage flexibility solutions can also provide voltage regulation services, black start services, avoid or delay network reinforcements by managing congestions, and capacity value by lowering the need for investments in conventional generation units.

Storage is particularly well-adapted in power systems with high shares of solar power, especially in cases where solar develops all across Europe. Indeed, since the solar generation patterns of Eastern and Western Europe are shifted by at most two hours, there is only a limited opportunity to export solar power to other countries, which is driven by the variability of cloud conditions.

Batteries are coming down in costs at a significant rate. Since their discharge time is typically of a couple of hours, their role can be particularly important in the provision of regulation services and are likely to increase their market penetration in the years to come, in particular at the residential level. The deployment of storage with longer discharge times is mainly limited by the Member State level potential to host PHS or CAES technologies.

Figure 7 provides a panorama of the main storage technologies, along with their typical power input/output and discharge time. More information can be found in "METIS Study S07 – The role and need of flexibility in 2030: focus on energy storage" and in the Commission Staff Working Document entitled "Energy storage - the role of electricity"[19].

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[19] SWD(2017) 61 final

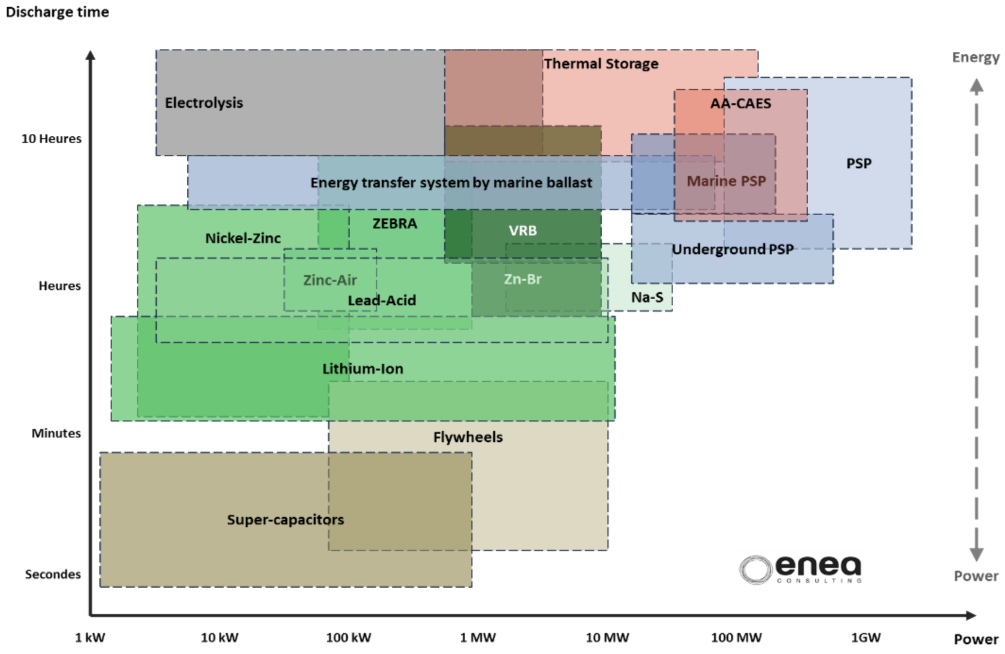

Figure 7 - Panorama of the main storage technologies

<u>List of techno-economic parameters (per storage technology)</u>

- Investment costs (in k€/MW)
- Operation and maintenance costs (in k€/MW/year)
- Efficiency (in %)
- Discharge time (in hours)
- Technical constraints: ramping rates, availability
- Potential (in MW, in particular for PHS and CAES)

Demand-response

Demand-response, or demand-side management, is a category of technologies that allow the demand-side to intentionally modify its consumption in response to price signals or other incentives from grid operators. Demand-response can be deployed in a number of sectors, among which the industrial, residential and transport sectors are probably the ones with the largest potentials. In most cases, residential and transport demand-response consist in delaying or shifting consumption (e.g. domestic hot water, white devices, electric vehicle battery charging, etc.), whereas in the industry, demand-response can also take the form of load shedding (e.g. an industrial process can in some cases be cancelled without repercussion on the demand of the following hours or days).

The potential role that demand-response can play at the Member State level mostly depends on the structure of the local industry, on the foreseen deployment of electric vehicles, and on the deployment of smart meters, which are required in order to provide price signals to the residential and commercial sectors (dynamic pricing) and to validate flexible demand-response transactions.

Provided the appropriate market conditions and regulatory frameworks are put in place, demand-response can provide a range of additional services such as congestion management, the provision of reserves, and capacity services (e.g. by being allowed to participate in capacity markets).

List of techno-economic parameters (per demand-response sector)

- Investment costs (in k€/MW)
- Operation and maintenance costs (in k€/MW/year)
- Activation costs (in €/MWh)
- Maximum load shifting/shedding duration (in hours)
- Maximum load shifting interval, minimum break time (in hours)
- Technical constraints: ramping rates, availability
- Potential (in MW)

Interconnectors

The European Union has identified interconnectors as being essential for completing the European internal energy market and for meeting the EU's climate and energy targets. By their very nature, interconnectors allow transmission system operators (TSOs), and in some cases private project developers, to exploit the complementarities between neighbouring electricity systems, both in terms of demand profiles and in terms of the structure of the generation mix.

Interconnectors can indeed allow the export of excess energy from one country to another, in particular since wind generation patterns do not tend to have as strong a correlation as PV patterns do. Moreover, a joint optimisation of the network and PV or wind energy geographical deployment can result in situations in which some countries with favourable weather conditions host more capacity than they would need at the national level, and export the excess energy to other countries.
More in general, interconnectors allow for a better use of baseload and mid-merit generation fleets, since they can increase their number of running hours compared to a case without interconnectors. A regional dimensioning of reserves can enhance this phenomenon even more, by allowing more baseload and mid-merit capacity to enter the wholesale market instead of procuring balancing reserves. As a consequence, the investments in peaking generation capacity in a strongly interconnected European power system can be substantially reduced compared to a situation without solidarity and cooperation.

List of techno-economic parameters (per interconnection project)

- Investment costs (in k€/MW)
- Operation and maintenance costs (in k€/MW/year)
- Losses/efficiency (in % of the scheduled flow)
- Technical constraints: ramping rates, availability
- Potential (in MW)

System-friendly RES-e technologies

One of the main challenges associated with variable RES-e technologies is related to the flexibility that has to be provided by the other market participants. One way to reduce the flexibility needs is to deploy PV and wind technologies whose profiles are easier to integrate (i.e. which have a lower contribution to flexibility needs for the same energy output). These technologies include: east-west oriented PV panels, advanced wind turbines, which have larger rotor diameter to capacity ratios enabling them to deliver higher outputs at low wind speeds.

List of techno-economic parameters (per technology)

- Investment costs (in k€/MW)
- Operation and maintenance costs (in k€/MW/year)
- Capacity factor (in %, with an hourly time resolution)
- Potential (in MW)

2.3.2 Publicly available data sources

This section provides a number of references to publicly available sources of data allowing to identify and characterise flexibility solutions at Member State level.

Flexible generation technologies

- The IEA-ETSAP Energy Technology Data Source provides rich descriptions of energy supply technologies. However, most of the documents were published a number of years ago and do not reflect the latest progress or trends.

  Link: https://iea-etsap.org/index.php/energy-technology-data

- In 2014, the European Commission's JRC has published Energy Technology Reference Indicator projections for 2010-2050 (ETRI). The ETRI contains most of the figures that are required to characterise flexible generation technologies such as OCGTs, CCGTs and hydropower.

  Link: https://setis.ec.europa.eu/related-jrc-activities/jrc-setis-reports/etri-2014

- The METIS database contains a number of characteristics of flexible generation technologies. The METIS documentation gathers the results of a literature review performed by Artelys. Minimum stable generation levels, gradients, starting costs, minimum off-time, and efficiencies can be found in Section 3.1.1.3 of "METIS Technical Note T2 – Power Market Models".

  Link: http://ec.europa.eu/energy/en/data-analysis/energy-modelling/metis

Storage

- The ETRI contains a section dedicated to storage technologies such as CAES, flywheel, a range of battery technologies, and PHS.

  Link: https://setis.ec.europa.eu/related-jrc-activities/jrc-setis-reports/etri-2014

- The JRC has published an assessment of the European potential for pumped hydropower energy storage in 2013, at the Member State level. This assessment is based on GIS techniques.

  Link: https://setis.ec.europa.eu/related-jrc-activities/jrc-setis-reports/assessment-of-european-potential-pumped-hydropower-energy

- The ESTMAP project, funded by the European Commission through the Horizon 2020 programme, has produced an online database of potential for subsurface and above-ground storage reservoirs, which is accompanied by a Country Energy

Evaluation report that provides the potentials for different technologies at Member State level.

Link: http://www.estmap.eu

Demand-response

- In 2016, DG ENER has published a study entitled "Impact assessment study on downstream flexibility, price flexibility, demand-response & smart metering", which presents demand-response potentials at the Member State level, based on the doctoral thesis of Hans Christian Gils.

  Link: https://ec.europa.eu/energy/sites/ener/files/documents/demand_response_ia_study_final_report_12-08-2016.pdf

- In 2015, RTE has published the study "Valorisation socio-économique des réseaux électriques intelligents" aiming at evaluating the value brought by smart-grid technologies, and demand-response in particular. The report provides a number of useful techno-economic assumptions.

  Link: http://www.rte-france.com/sites/default/files/rei_bd_1.pdf (in French)

Interconnectors

- Most of the interconnection projects at the European level are described by ENTSO-E in the datasets published along the TYNDP 2016. The TYNDP "Combined project sheets" contains the main characteristics of each of the projects: capacity, cost, expected commissioning date. Note that not all interconnection projects are listed in the TYNDP 2016 (e.g. NeuConnect) and that the 2018 version of the TYNDP should be published shortly after the publication of this report.

  Link: http://tyndp.entsoe.eu

System-friendly RES-e technologies

- In their article, Lion Hirth and Simon Müller present the economics of advanced wind turbines. The article compares the performance of two wind turbines at low wind speeds, and the influence on the ability of these technologies to capture market revenues.

  Link: https://doi.org/10.1016/j.eneco.2016.02.016

- The wind-turbine-models website gathers the power curves of a large set of commercially available wind turbines.

  Link: https://www.en.wind-turbine-models.com/powercurves

- In June 2016, the IEA Wind has published a report based on a survey of wind energy experts that presents the current understanding of future wind energy costs and potential technological advancement.

  Link: https://www.ieawind.org/task_26.html

2.4 Step 3 - Optimisation of the flexibility portfolio

The third and final step of the recommended methodology consists in optimising the composition of the portfolio of flexibility solutions, by taking into account the costs, operational constraints and potentials identified previously (*Step 2*). The resulting flexibility portfolio will be able to cover the flexibility needs that have been computed from the analysis of the residual load (*Step 1*).

In order to capture all the phenomena described previously, the model to be used should ideally have the following characteristics:

- **Hourly time resolution** – Since the role of the model is to determine which combination of technologies one should select so as to be able to provide the system with the ability to ramp up and down fast enough to cope with the demand and variable RES-e generation fluctuations, it is essential that the model is able to represent the dynamics of the system (demand and variable RES-e generation profiles) with an hourly time resolution at least.

- **Annual time horizon** – In order to capture all the flexibility needs, including long-term ones such as those driven by seasonal effects such as heating and cooling, the model should be able to represent the whole year. Analyses based on typical days or weeks fail to represent the weekly and annual management of storage capacities, and should therefore be avoided for such exercises. We recommend to use a model able to explicitly represent the whole year with an hourly time resolution (i.e. 8760 time-steps per year).

- **Regional modelling** – The model has to explicitly represent neighbouring countries and allow for dynamic (i.e. not fixed) exchanges of power with them. If this requirement is not met, the model will likely overestimate the investments that are needed to cover the demand, as it does not take into account mutual assistance and cooperation between Member States.

- **Joint optimisation of investments and operations** – The model should be able to endogenously determine the optimal set of investments in flexibility solutions. Using pure simulation models can provide a number of indications on the performance of a given set of investments, but would be of limited help to to find the optimal trade-off between a potentially large number of options (flexible generation technologies, storage technologies, demand-response schemes, interconnection projects, etc.)

If possible, the model should be able to represent multiple weather scenarios, which are translated into demand variations (via a load-temperature sensitivity analysis) and solar and wind generation variations. Basing the computation of the optimal portfolio of flexibility solutions on several annual weather scenarios ensures the analysis is robust, and is not biased by using the data of a single historical year. In the application of the methodology presented in Section 3, we use 50 weather scenarios to ensure the resulting power system is able to face challenging weather conditions (e.g. dry year, cold winters, long periods with low wind availability, etc.).

An explicit representation of the reserve procurement can also be valuable, but is not essential. By representing sub-hourly flexibility needs, one may ensure that the resulting power system is able to cover the demand, and has an adequate capacity to face unforeseen imbalances. Since upwards balancing reserves can drive the need for additional capacity, it is found to be sufficient in most cases to restrict to the representation of upwards regulation services and to neglect the provision of downwards balancing reserves.

Recommended modelling procedure

In order to determine the optimal 2030 portfolio of flexibility solutions, we recommend to adopt the following procedure:

- The minimum capacities of flexibility solutions should be set at their residual value (i.e. the capacity of these technologies that is currently installed and that will still be operational in 2030)
- The capacity of other generation technologies, including RES-e technologies, should be based on a scenario, such as the METIS EUCO30 scenario that is used in the application presented in Section 3. A joint optimisation of the flexibility solutions and RES-e deployment can also be relevant, in particular to have a well-balanced portfolio of RES-e technologies (with different generation profiles) and available flexibility solutions.

The other modelling inputs include:

- Electricity and reserve demands
- Investment costs for each of the considered flexibility solutions that include both CAPEX (capital expenditure) and O&M (operation and maintenance) costs. If the model uses an annual time horizon, the investment costs should be annualised. In the application presented in Section 3 we have used a 4% discount rate[20].
- Fuel and CO_2 prices for all technologies
- Technical characteristics for all technologies
- An adequacy criterion, that can either be a number of hours of loss of load expectation, or a value of loss of load (15 k€/MWh in our case).

This output of the optimisation includes the hourly electricity and reserve dispatch at the national level over the considered region (Europe in our case) and the optimal set of flexibility solutions.

In the application presented in Section 3, we have selected Artelys Crystal Super Grid to optimise the portfolio of flexibility solutions. Thanks to its state-of-the-art capacity expansion planning module and decomposition algorithms, Artelys Crystal Super Grid has been able to optimise investments over the 34 countries, over 50 annual weather scenarios with an hourly time-resolution.

[20] http://ec.europa.eu/smart-regulation/guidelines/tool_54_en.htm

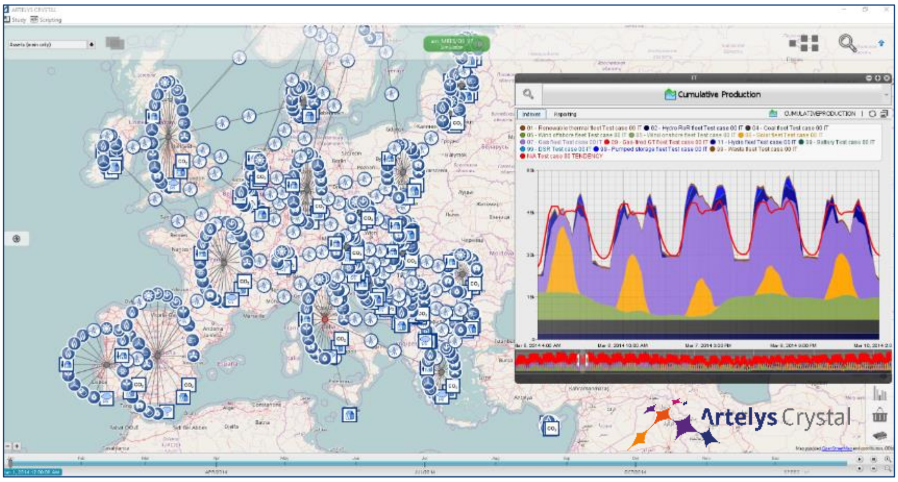

Figure 8 - The METIS EUCO30 scenario in Artelys Crystal Super Grid

3 Application of the framework at the European level

This section aims at applying the methodology set out in Section 2. We first analyse the flexibility needs at Member State level and their evolution between 2020 and 2030, we then identify and characterise flexibility solutions at the Member State level, and finally proceed with the computation of the optimal flexibility portfolio at the Member State level.

In particular, we illustrate that it is beneficial to allow demand-response, storage and interconnectors to participate in the provision of flexibility, rather than only relying on thermal generation. This result further stresses the need for a level playing field among technologies, and the role of regional cooperation among Member States. The application of the recommended framework is based on the METIS EUCO30 scenario, which is introduced below.

3.1 The METIS EUCO30 scenario

The METIS EUCO30 scenario is based on the PRIMES EUCO30 scenario[21], which is a core scenario developed as part of the European Commission's impact assessment work in 2016. The PRIMES EUCO30 scenario is designed to meet all the 2030 targets set by the European Council in 2014[22], and reaches a more ambitious level of energy efficiency of 30% compared with the 27% target adopted by the Council.

The following data from the PRIMES EUCO30 scenario is inherited by the METIS EUCO30 scenario:

- Annual demand at MS-level
- Primary energy prices
- CO_2 price
- Installed capacities at MS-level
- Interconnection capacities

The METIS versions of PRIMES scenarios include refinements on the time resolution (hourly time resolution) and unit representation (explicit modelling of reserve procurement). For more details on the way METIS versions of PRIMES scenarios are built, we refer the reader to the METIS Technical Note T1[23].

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21 DG ENER, Energy modelling webpage - https://ec.europa.eu/energy/en/data-analysis/energy-modelling

22 European Council conclusions, 23/24 October 2014

23 Artelys, "*METIS Technical Note T1 – Methodology for the integration of PRIMES scenarios into METIS*", 2016

The 2030 METIS EUCO30 scenario corresponds to a vision of Europe[24] in 2030 characterised by a large share of renewables. Overall, RES-e production amounts for almost 50% of the demand in this scenario. Figure 9 presents the annual shares of the demand being met by wind and solar energy at the Member State level in this scenario.

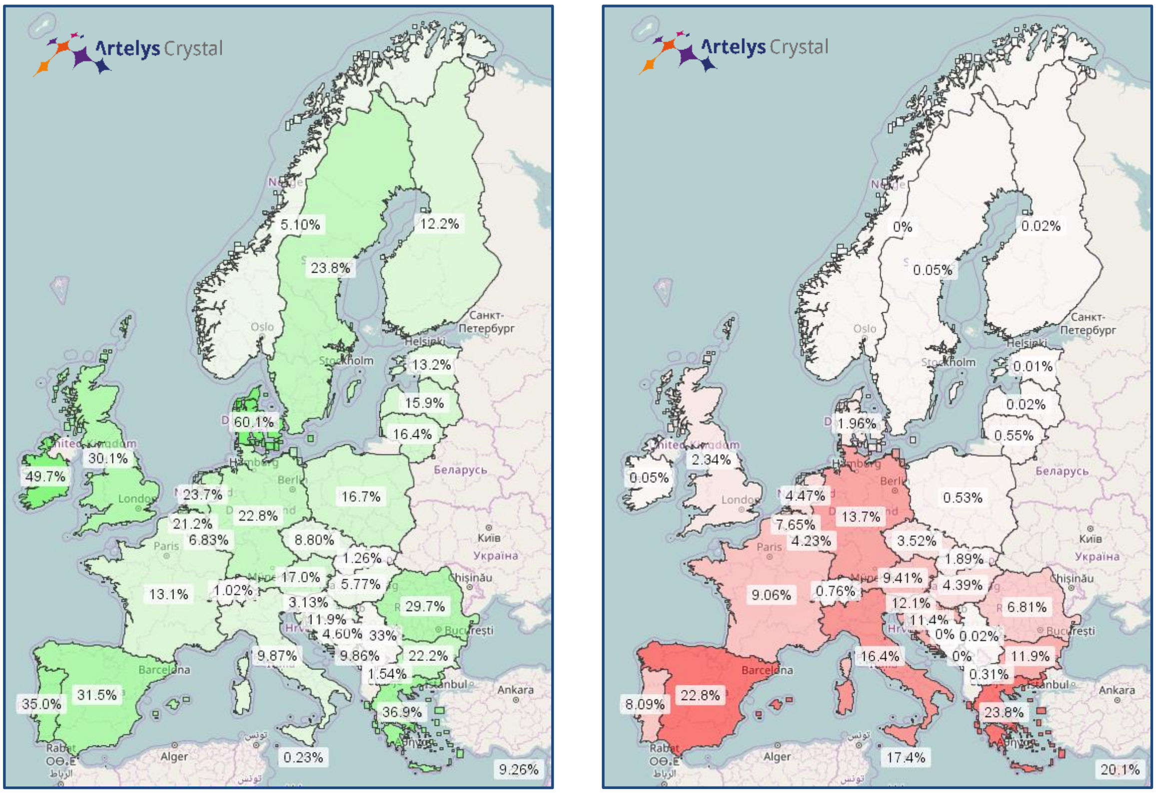

Figure 9 - Shares of wind (left) and PV (right) in demand in the 2030 METIS EUCO30 scenario

The price of CO_2 in the 2030 METIS EUCO30 is set at 27€ per tonne and is not adjusted for the different options assessed. As a result of the assumed carbon price and fuel prices, coal- and lignite-fired units are found to have lower production costs than gas-fired units. As a consequence, measures that allow for a better exploitation of cheap resources (baseload and mid-merit) will result in an increased use of RES-e (less curtailment), and of nuclear, coal, and lignite units.

Moreover, the scenario assumes a regional dimensioning of reserves. The model therefore has to find the optimal trade-off between a local provision of reserves and the reservation of interconnection capacity to share reserves among Member States[25].

Finally, in order to ensure the robustness of the analysis, 50 weather scenarios have been generated with the Artelys Crystal Forecast tool[26]. Weather scenarios contain

[24] The model covers the EU28, Norway, Switzerland, Bosnia-Herzegovina, the Republic of Serbia, Montenegro and the Former Yugoslav Republic of Macedonia.

[25] For more details, see the analysis by Artelys in COWI, "*Integration of electricity balancing markets and regional procurement of balancing reserves*", 2016 and Artelys, "*METIS Study S12 - Assessing Market Design Options in 2030*", 2016.

[26] https://www.artelys.com/en/applications/artelys-crystal-forecast

information on the temperature, wind capacity factors and solar capacity factors at the Member State level. The geographical and temporal correlation of the temperature and of the wind and solar capacity factors have been calibrated on historical data. An analysis of the load-temperature sensitivity at Member State level has allowed us to assess the impact of the temperature on the demand.

3.2 Step 1 - Evaluation of flexibility needs

The first step of the recommended methodology as set out in Section 2 is to evaluate the need for flexibility on three different timescales: daily, weekly and annual flexibility needs are to be evaluated.

As mentioned in Section 2.2, this computation requires a demand time-series, and the solar, wind and must-run generation time-series at the Member State level. In our application, we have used the METIS EUCO30 time-series for 2020 and 2030. In order to generate the 2025 time-series, we have exploited the 2025 annual demand, PV and wind generation of PRIMES EUCO30 and have combined them with averaged 2020 and 2030 profiles so as to take into account technological progress of solar and wind technologies, and the evolution of the dynamics of the demand.

The flexibility needs presented in this section are found by averaging the value of the indicators over the 50 weather scenarios.

Daily flexibility needs

The daily flexibility needs at Member State level are shown on Figure 10 for 2020, 2025 and 2030. Unsurprisingly, daily flexibility needs tend to increase in most Member States. At the EU28 level, the daily flexibility needs increase by around 26% over the 2020-2030 period.

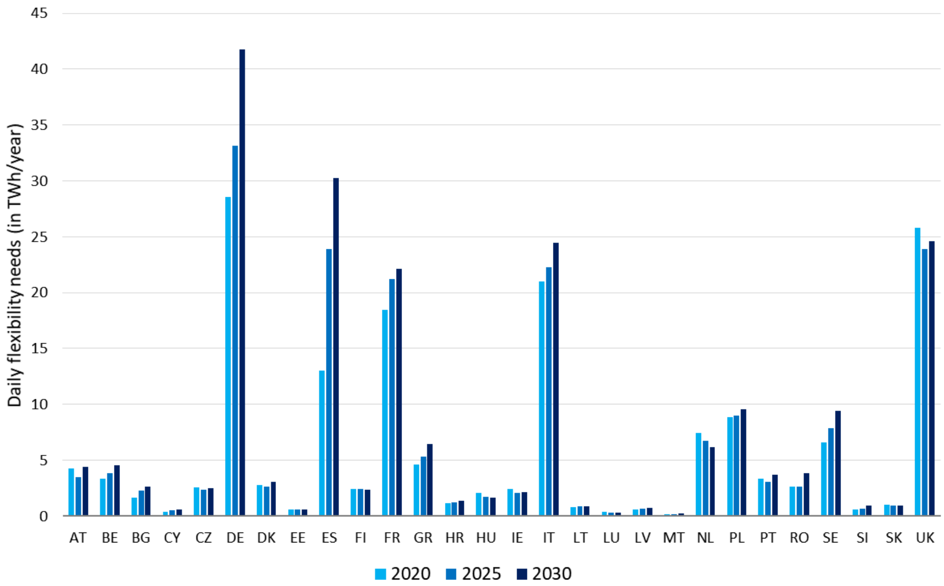

Figure 10 - Trajectory of daily flexibility needs

We observe that, although daily flexibility needs increase overall in Europe, the trajectory followed by these needs strongly differs from one Member State to the other. For example, the Spanish daily flexibility needs rise from 13 TWh per year in 2020 to

30 TWh per year in 2030 (+133%) while the French ones only increase from 18 TWh per year in 2020 to 22 TWh per year in 2030 (+20%). In some Member States, the daily flexibility needs are even found to decrease (e.g. in Hungary). Figure 11 illustrates the diversity of evolutions of the daily flexibility needs over the 2020-2030 period at the Member State level.

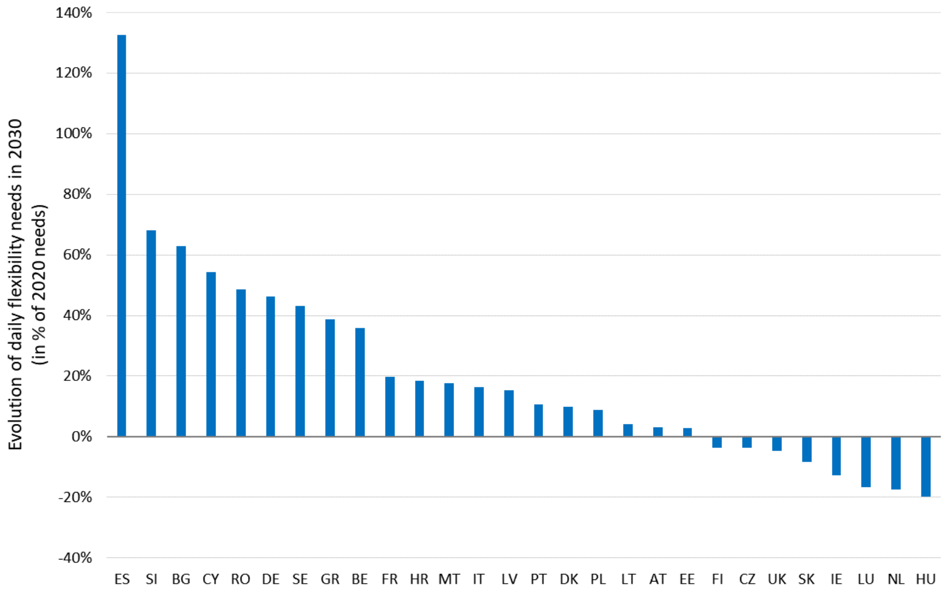

Figure 11 - Evolution of daily flexibility needs between 2020 and 2030

Although surprising at first sight, these results can be explained by a single factor: the share of demand that is met by solar power. Indeed, due to the daily solar cycle, the share of PV has a considerable influence on the daily flexibility needs:

- **Low level of solar installed capacity –** When one starts from a situation with a very low amount of solar generation (compared to the demand), an increase of solar capacity leads to a decrease of flexibility needs. Indeed, since solar generation is usually well correlated with the demand, the penetration of the first MWs of solar capacity tends to erase the demand peak, resulting in a smoother residual load pattern and lower daily flexibility needs.

- **High level of solar installed capacity –** When solar capacity increases above a MS-dependent threshold, the further penetration of solar capacity results in the apparition of a valley in the residual load.

This phenomenon, also known as the duck curve challenge, is illustrated by Figure 12, which shows the demand (solid blue line) and residual loads for different solar capacity deployment.

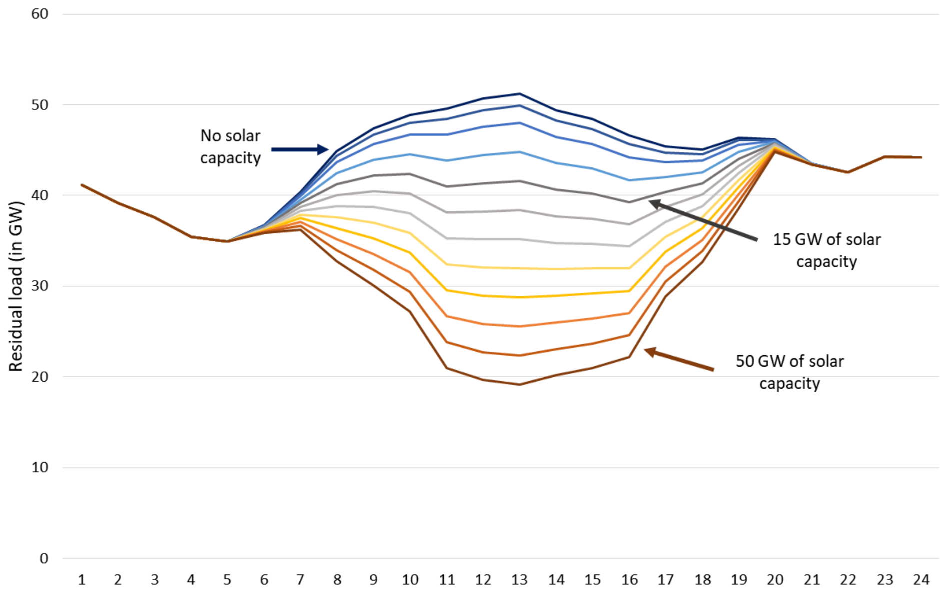

Figure 12 – Illustration of the impact of solar capacity deployment on the residual load

Figure 13 shows the sensitivity of daily flexibility needs to the share of solar generation in the national demand for Hungary, Spain and France. One can observe the behaviour described above: daily flexibility needs first decrease until the share of solar generation is below around 5% of the demand, at which point they begin to increase as the valley in the residual load deepens.

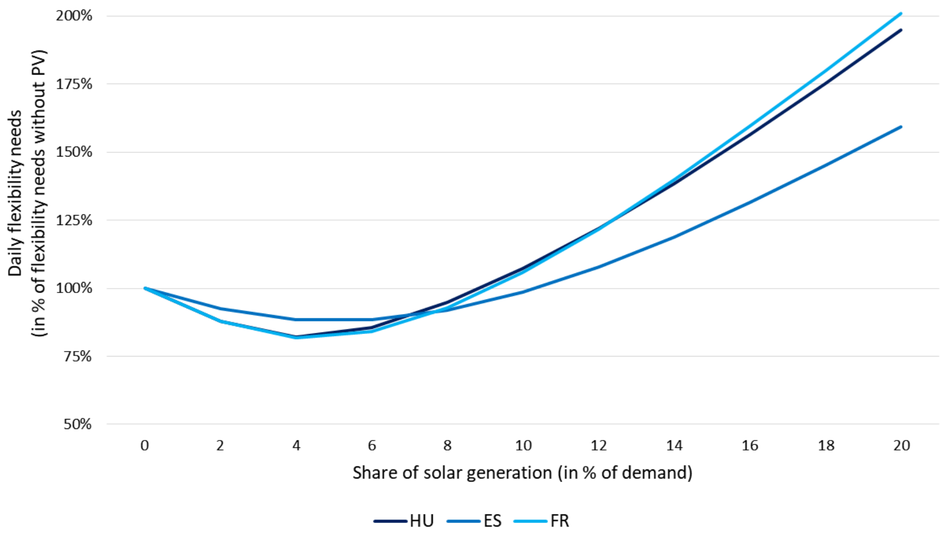

Figure 13 - Sensitivity of daily flexibility needs to the share of solar generation

We can now understand why France and Hungary, whose daily flexibility needs have very similar behaviours as a function of share of solar generation (see Figure 13), have different daily flexibility needs trajectories (see Figure 11).

Indeed, as shows in Table 4, the 2020 share of solar capacity in France is already above the threshold, so that the increase of the French solar capacity between 2020 and 2030 results in an increase of its daily flexibility needs. In the case of Hungary, both the 2020 and 2030 shares are below the threshold. This explains why the daily flexibility needs decrease even if the solar capacity increases in Hungary.

Member State	Share of solar in 2020 (in % of demand)	Share of solar in 2030 (in % of demand)
France	6.2%	9.1%
Hungary	0.2%	4.4%
Spain	5.8%	23%

Table 4 - 2020 and 2030 shares of solar generation (in % of annual demand)

One can finally note that the Spanish daily flexibility needs are less sensitive to the share of solar generation in the demand, thanks to the presence of air conditioning, whose utilisation pattern is well correlated with the daily solar cycle.

Weekly flexibility needs

The weekly flexibility needs at Member State level are shown on Figure 14 for 2020, 2025 and 2030. Unsurprisingly, weekly flexibility needs tend to increase in most Member States. At the EU28 level, the weekly flexibility needs increase by around 27% over the 2020-2030 period.

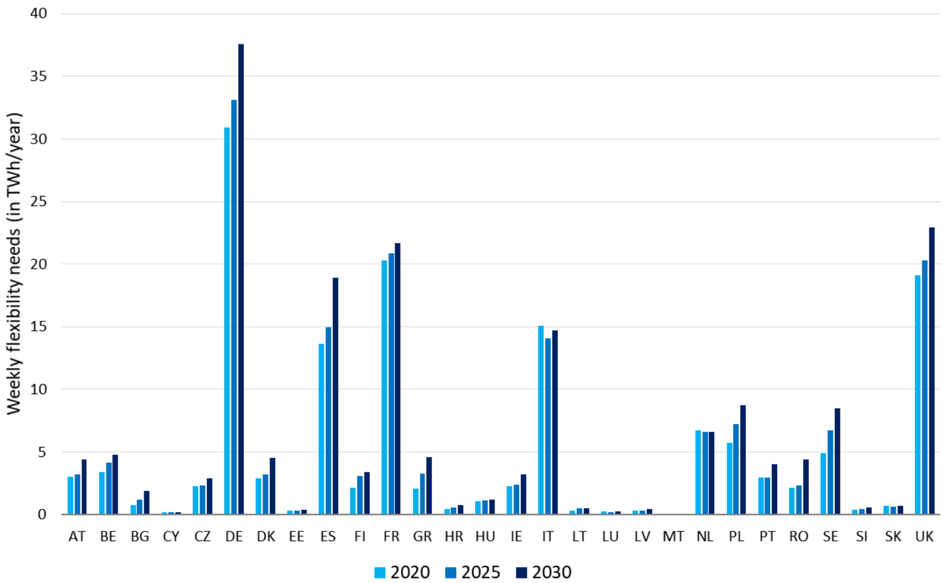

Figure 14 - Trajectory of weekly flexibility needs

While they increase in almost every Member State, the evolution pace is very different from one Member State to the other. Indeed, as can be read from Figure 15, weekly flexibility needs increase by more than 100% in Romania, more than 120% in Greece and 140% in Bulgaria. A number of countries, as Austria and Latvia, see their weekly flexibility needs increase by around 45% to 60%. Finally, some countries such as France, Slovakia or Italy see their weekly flexibility needs evolve only very moderately.

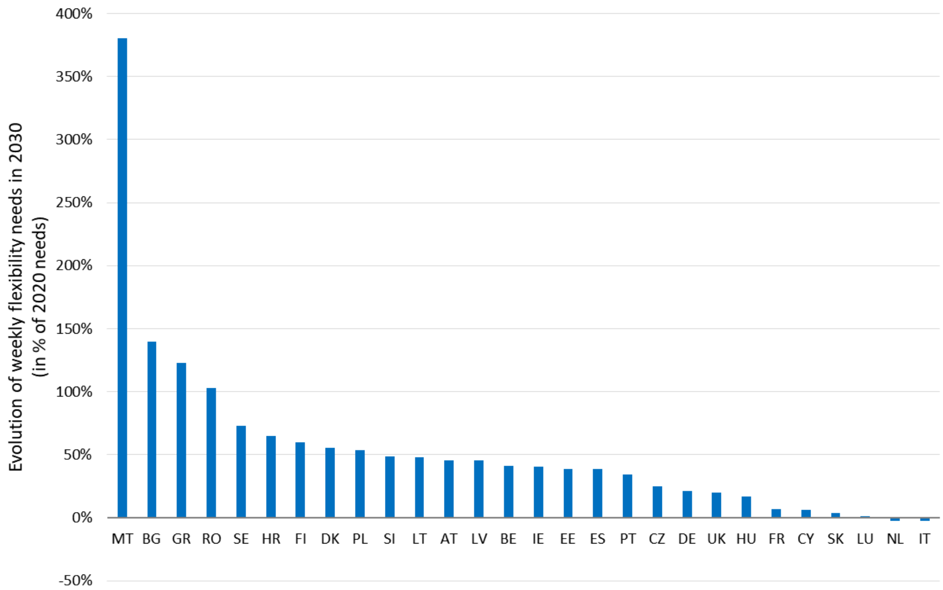

Figure 15 - Evolution of weekly flexibility needs from 2020 to 2030

The 2020-2030 evolution of weekly flexibility needs is mainly driven by the raising share of wind generation in the energy mix. Indeed, flexibility needs are sensitive to the share of wind energy (wind regimes typically vary over periods of a few days). As the proportion of the EU28 electricity demand being served by wind power moves from 14% in 2020 to 21% in 2030, the weekly flexibility needs are found to increase too. Figure 16 illustrates how weekly flexibility needs vary as the share of the demand being met by wind power increases for Bulgaria, Spain and France.

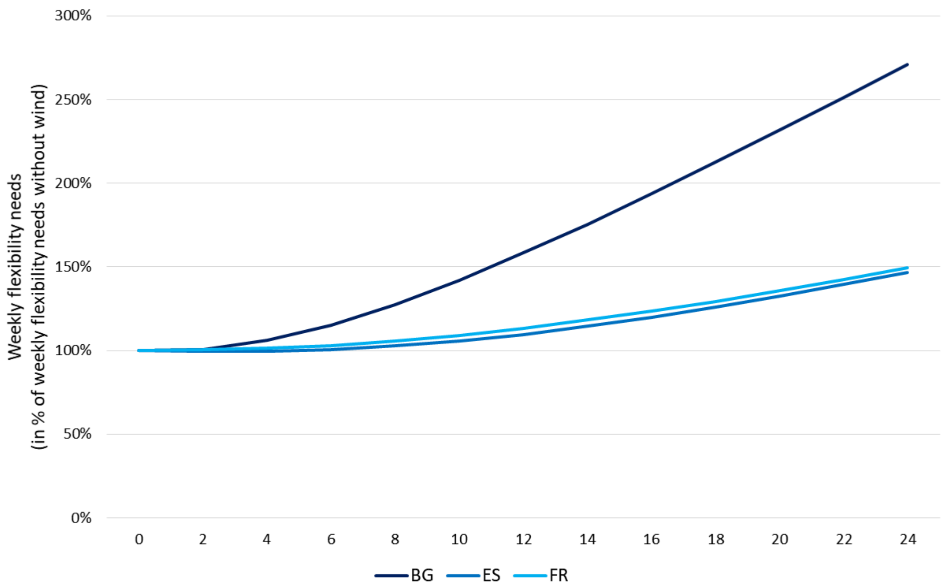

Figure 16 - Weekly flexibility needs sensitivity to the share of wind generation

In the absence of wind, the weekly flexibility needs are driven by the fact that the electricity consumption has a clear weekday-weekend pattern. This pattern is itself a function of the structure of the economy since, for example, the tertiary sector tends to have a larger weekday-weekend contrast that the industry. Note that the weekday-weekend pattern can also be influenced by the presence of price signals that incentivise some consumers to shift their use during the weekend.

One can observe that the Member States with the highest increase in weekly flexibility needs over the 2020-2030 period, such as Bulgaria and Greece, are characterised by a very high sensitivity of their weekly flexibility needs to the share of wind generation (see Figure 16 in the case of Bulgaria). Moreover, the shares of wind power in the national demands of these countries increase by almost 20 percentage points in Bulgaria and by almost 30 percentage points in Greece. The combination of these two elements drive the significant increase of weekly flexibility needs displayed by these Member States.

Member State	Share of wind in 2020 (in % of demand)	Share of wind in 2030 (in % of demand)
Bulgaria	3.5%	22.2%
Germany	19.3%	22.9%
Spain	20.4%	31.7%
France	10.8%	13.1%
Greece	8.7%	36.9%

Table 5 - 2020 and 2030 shares of wind generation (in % of annual demand)

Annual flexibility needs

Finally, the annual flexibility needs at Member State level are shown on Figure 17 for 2020, 2025 and 2030. At the EU28 level, the annual flexibility needs increase by around 14% over the 2020-2030 period.

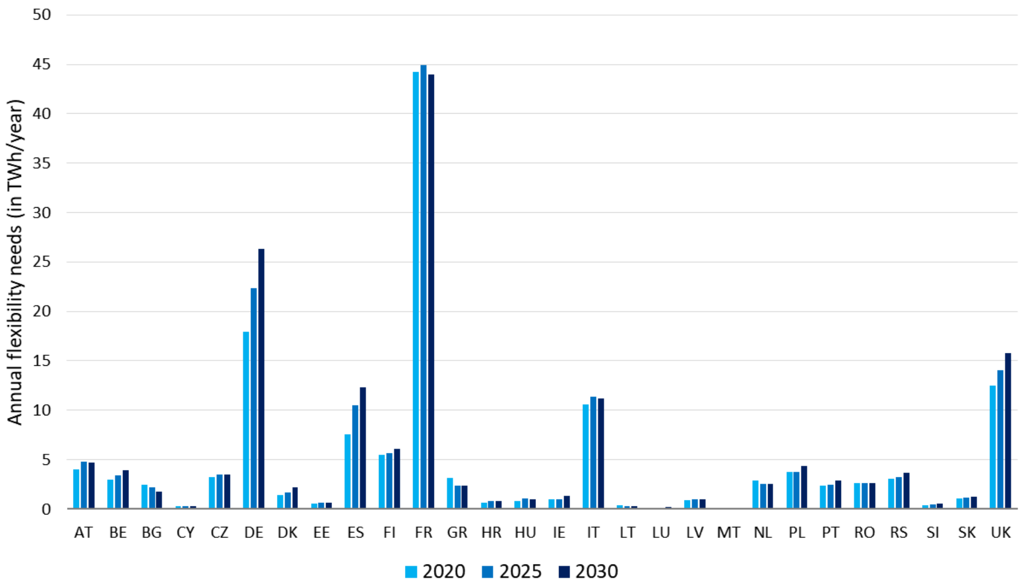

Figure 17 - Trajectory of annual flexibility needs

In contrast with the daily and weekly flexibility needs, there is no single driver that can explain most of the observed evolution of the annual flexibility needs. Indeed, the following effects can have counteracting impacts:

- **Demand** – The evolution of the load-temperature sensitivity can vary from one Member State to the other. The electrification of heat can drive the seasonal load variation and thus increase the annual flexibility needs in some countries (due to the replacement of gas heating by heat pumps for example), but this can be counter-balanced by efforts in energy efficiency or by technology shifting (e.g. from electric space heaters to heat pumps). The penetration of air conditioning in Southern European countries can also impact the annual flexibility needs.

- **Solar** – Solar production is higher during the summer period, and lower during wintertime. A large penetration of solar power can therefore increase the annual flexibility needs in most countries, as illustrated below in the case of Germany. In Southern countries such as Greece, the demand can be higher during summertime due to air conditioning, leading to solar penetration having a positive impact on the annual flexibility needs (reduction).

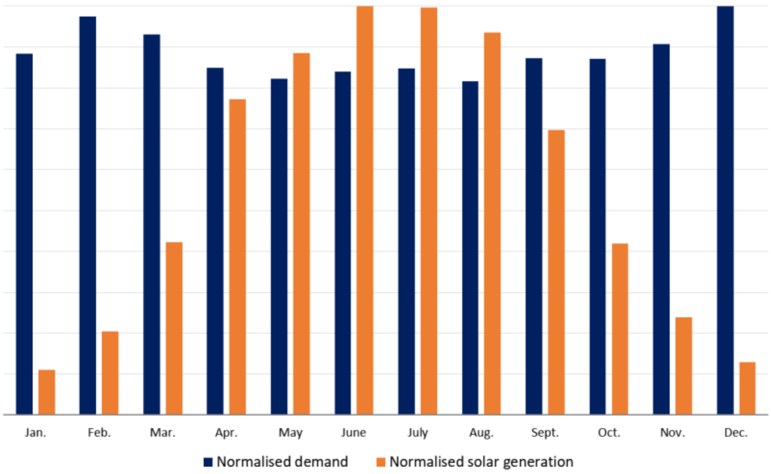

Figure 18 - Monthly demand and solar generation in Germany in 2030

- **Wind** – Wind production, in contrast with solar, tends to be higher during winter than during summer. A large penetration of wind power can therefore decrease the annual flexibility needs in most countries, as is illustrated below in the case of Germany.

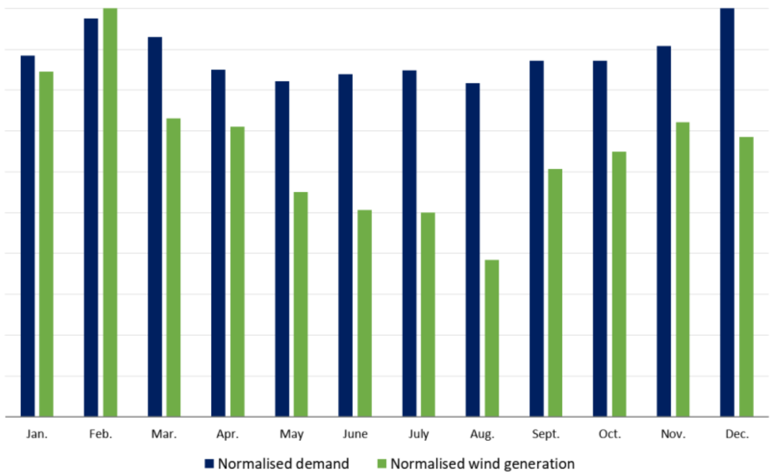

Figure 19 - Monthly demand and wind generation in Germany in 2030

3.3 Step 2 - Identification and characterisation of the local flexibility solutions

The second step of the recommended methodology as set out in Section 2 is to identify and characterise flexibility solutions. As mentioned in Section 2.3, flexibility can be provided by various technologies: flexible generation technologies, storage, demand-response, interconnectors, etc. In the following, we present the assumptions used for our study of the optimal portfolio of flexibility solutions at the European level. Annuities are calculated using a 4% discount rate[27].

Flexible generation technologies

The flexible generation technologies that we consider in our study include coal- and gas-fired units. We allow the model to invest in state-of-the-art gas units (CCGTs and OCGTs), without any restriction (no maximum investment constraint). Furthermore, existing coal units and CCGTs can be retrofitted to improve their flexibility.

Table 6 summarises our assumptions regarding the main characteristics of the considered flexible generation technologies. All the technical characteristics (ramping rates, minimum stable generation, etc.) can be found in the METIS Technical Note T1[28].

Flexibility solution	Description	Investment cost[29]	Fixed operating costs per year[30]
State-of-the-art OCGT	Addition of state-of-the-art OCGT capacity	550 k€/MW	3.0% of inv. costs
State-of-the-art CCGT	Addition of state-of-the-art CCGT capacity	850 k€/MW	2.5% of inv. costs
Retrofitting CCGT	Retrofitting existing CCGT capacity: • Minimum load decreases from 50% to 40% of running capacity • Starting costs decreases from 45 to 33€/MW	3.2 k€/MW	2.5% of inv. costs
Retrofitting Coal	Retrofitting existing CCGT capacity: • Minimum load decreases from 40% to 25% of running capacity • Starting costs decreases from 65 to 50 €/MW	3.4 k€/MW	2.5% of inv. costs

Table 6 - Characteristics of flexible generation technologies

Storage

Three different types of storage technologies with different discharge times are considered in our study.

Pumped Hydro Storage (PHS) is a versatile solution to increase storage capacity, but its potential varies considerably from Member State to Member State. We assume new PHS units to have an 8-hour discharge time and consider that investments in larger hydro plants are less likely due to environmental regulations and public acceptance. The PHS

[27] http://ec.europa.eu/smart-regulation/guidelines/tool_54_en.htm

[28] Artelys, "*METIS Technical Note T1 - METIS Power Market Models*", 2016

[29] Sources: JRC, "*Energy Technology Reference Indicator projections for 2010-2050*", 2014 and NREL, "*Cost-Benefit Analysis of Flexibility Retrofits for Coal and Gas-Fueled Power Plants*", 2013

[30] Source: JRC, "*Energy Technology Reference Indicator projections for 2010-2050*", 2014

potential is divided into two categories: low-cost PHS with two existing reservoirs and high-cost PHS with only one existing reservoir (which would require the construction of another reservoir).

Figure 20 shows the PHS potential at the Member State level for the low-cost option[31]. The potential for high-cost PHS is much higher, but will be shown never to be exploited.

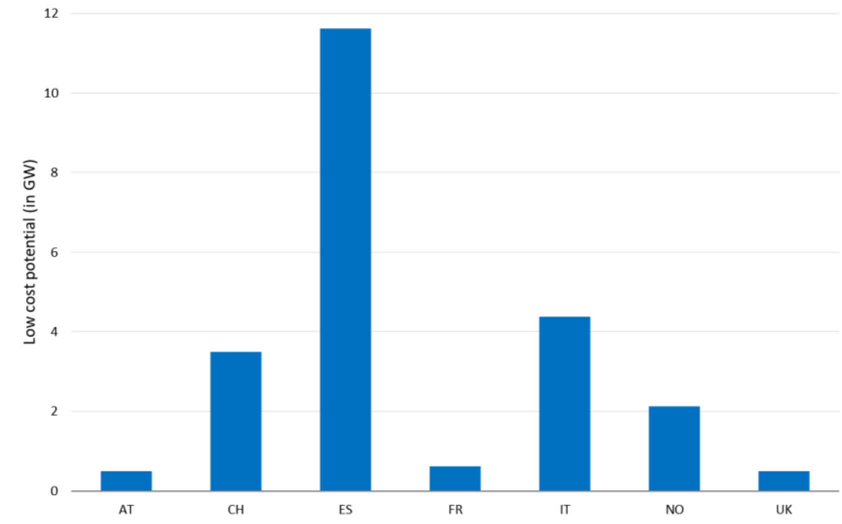

Figure 20 - Low-cost PHS potential per country

Compressed Air Energy Storage (CAES) with discharge times that are longer that PHS (we assume a discharge time of 48 hours for CAES) are considered in this study. The potentials, which again considerably vary from country to country, have been extracted from the ESTMAP database[32] and are shown on Figure 21.

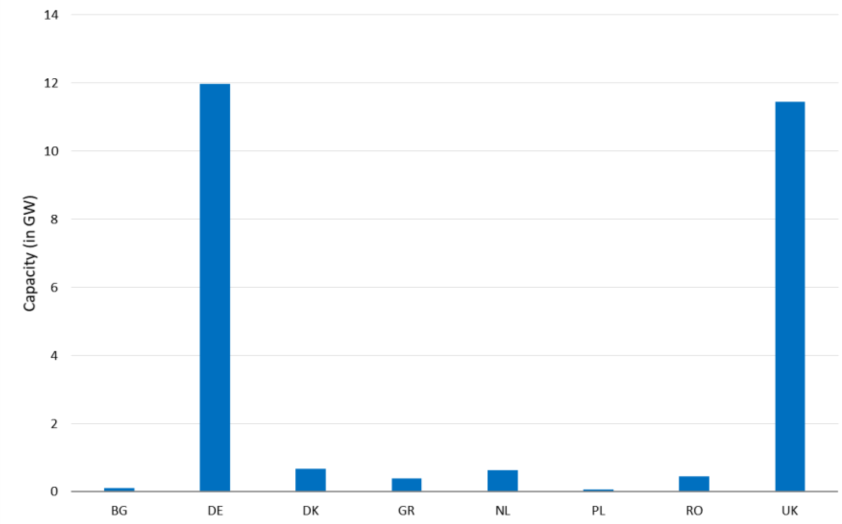

Figure 21 - Potential for CAES per country

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[31] Source: JRC, "*Assessment of the European potential for pumped hydropower energy storage*", 2013

[32] ESTMAP, "*Country Energy Storage Evaluation*", 2017

Finally, *batteries* are considered to propose a small scale storage solution and participate in the provision of sub-hourly flexibility. In this study, all batteries are modelled with one-hour discharge time. We do not assume any restrictions on the deployment of batteries.

Table 7 summarises our assumptions regarding the main characteristics of the considered storage technologies.

Flexibility solution	Description	Investment cost[33]	Fixed operating costs per year[34]
Low-cost PHS	Pumped Hydro Storage with two existing reservoirs • Discharge duration : 8 hours	810 k€/MW[35]	1.5% of inv. costs
High-cost PHS	Pumped Hydro Storage with one existing reservoir • Discharge duration : 8 hours	1 800 k€/MW[35]	1.5% of inv. costs
CAES	Compressed Air Energy Storage • Discharge duration : 48 hours	2 100 k€/MW[35]	1.5% of inv. costs
Batteries	Lithium-ion batteries • Discharge duration : 1 hour	400 k€/MW[36]	1.4% of inv. costs

Table 7 - Characteristics of storage flexibility solutions

Demand-response

Two types of demand-side response management plan were considered.

Industrial peak shaving is a solution which enables the curtailment of a part of demand. The price for industrial peak shaving is set at 300€/MWh[37]. The ability to use industrial peak shaving can prevent investments in additional thermal capacity that would only be used few hours a year.

Load shifting is used to reallocate part of the demand from one hour to another and to balance the grid. It is expected to contribute to hourly and daily flexibility needs. Figure 22 presents the potential for both demand-response schemes[38].

[33] Sources: ESTMAP, "*Country Energy Storage Evaluation*", 2017 and advice from the Advisory Board

[34] Sources: ESTMAP, "*Country Energy Storage Evaluation*", 2017 and JRC, "*Energy Technology Reference Indicator projections for 2010-2050*", 2014

[35] In addition, country-dependent connection costs are added to investment costs. Source: ESTMAP, "*Country Energy Storage Evaluation*", 2017

[36] Connection costs are assumed to be included in the battery investment costs.

[37] Source: RTE, "Valorisation socio-économique des réseaux électriques intelligents", 2015

[38] Source: COWI, "*Impact assessment study on downstream flexibility, price flexibility, demand-response & smart metering*", 2016

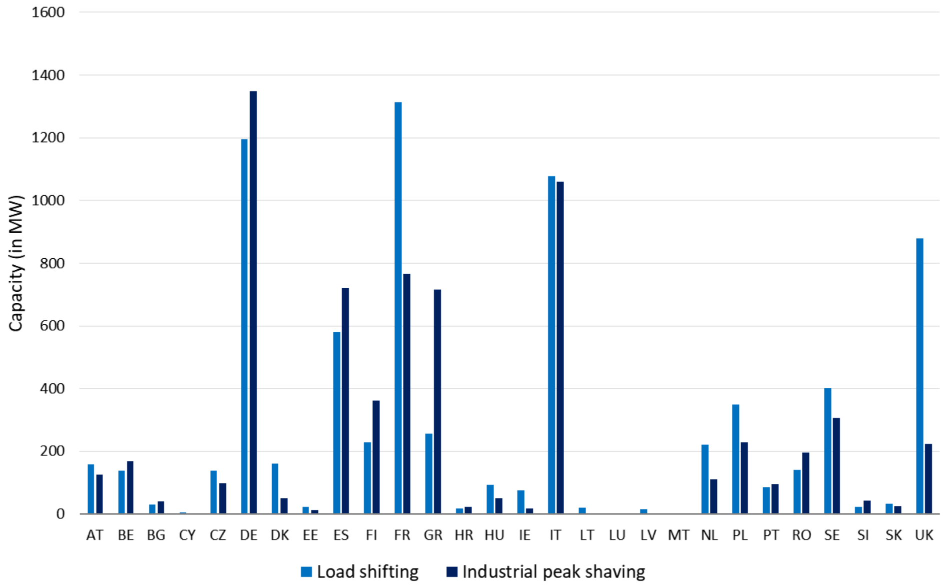

Figure 22 – Demand-response potentials

Table 8 presents the investments and operational costs of the considered demand-response technologies.

Flexibility solution	Description	Investment cost[39]	Fixed operating costs per year
Industrial peak shaving	Decreases the demand at cost of 300€/MWh.	15 k€/MW/year	6 k€/MW/year
Load shifting	Shifts demand to another hour.	34 k€/MW/year	4 k€/MW/year

Table 8 - Characteristics of demand-response flexibility solutions

Interconnectors

The characteristics of the latest list of Projects of Common Interest[40] (PCI) were extracted from ENSTO-E TYNDP 2016[41] to represent the potential for additional investments that increase the transfer capacity between neighbouring countries. All projects with either "planning" or "permitting" status are selected as potential investments. All the projects with status "under construction" are included in the capacity that is assumed to be operational by 2030. Figure 23 presents the potential for additional interconnection projects that has been assumed in this study.

[39] Source: RTE, "Valorisation socio-économique des réseaux électriques intelligents", 2015

[40] Regulation (EU) No 2016/89 of 18 November 2015 amending Regulation (EU) No 347/2013 of the European Parliament and of the Council as regards the Union list of projects of common interest

[41] The TYNDP datasets are available on the TYNDP webpage - http://tyndp.entsoe.eu

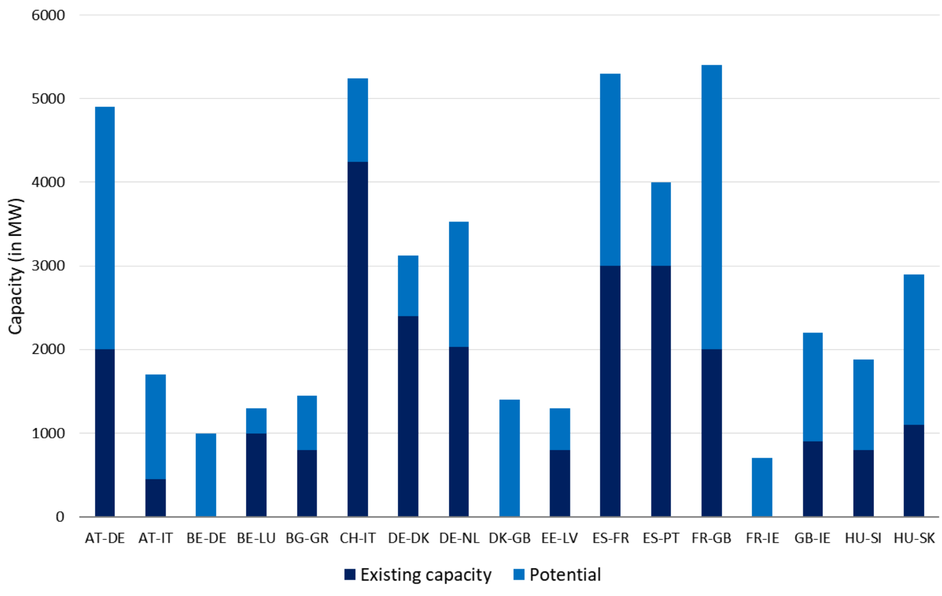

Figure 23 - Considered potential for additional interconnectors

The cost of each project was extracted from the ENSTO-E TYNDP 2016. When there are several projects across the same border, we consider the cost as being given by the weighted average cost over all projects. Figure 24 presents the annuities associated with each of the potential interconnection projects, assuming a discount rate of 4% over 25 years[42], and annual operation and maintenance costs corresponding to 1.5% of the investment cost.

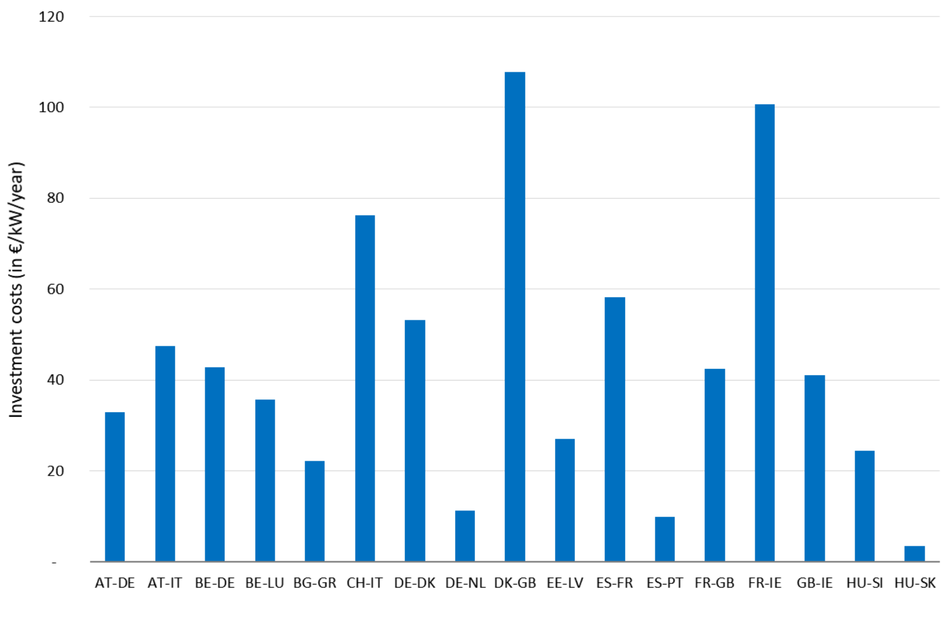

Figure 24 - Cost of interconnectors per couple of country

[42] See ACER Opinion No 05/2017 of 6 March 2017

System-friendly RES

System-friendly wind turbines can significantly reduce flexibility needs. Advanced turbines have the ability to better exploit low wind speeds. Therefore, they reach their maximal capacity quicker than conventional wind turbines and their generation profile shows a lower level of fluctuation, thereby decreasing flexibility needs. The difference between the capacity factors of conventional and advanced wind turbines as a function of wind speed is shown on Figure 25.

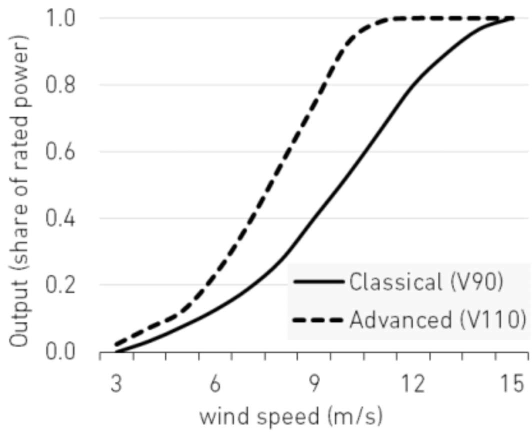

Figure 25 - Power generation according to wind speeds per turbine type. Source: Hirth, Lion & Simon Müller (2016): "System-friendly wind power: How advanced wind turbine design can increase the economic value of electricity generated through wind power", Energy Economics 56, 51-63

When applying the methodology, we consider the Vestas V90 turbine as being representative of conventional wind turbines and the Vestas V110 as our model of advanced wind turbines. After an assessment of the literature, it emerged that, at the European level, advanced and conventional wind turbines can be assumed to have similar LCOEs. Given the ability of advanced wind turbines to reduce flexibility needs, in particular on weekly timescales, advanced onshore wind turbines are found to be more system-friendly than conventional ones.

3.4 Step 3 - Optimisation of the flexibility portfolio

The third and final step of the recommended methodology as set out in Section 2 is to use a model to optimise the portfolio of flexibility solutions. We have selected the Artelys Crystal Super Grid model for this study. This model allows us to optimise the portfolio of flexibility solutions at the Member State level (in total, 34 countries are represented in the model), with an hourly time-resolution over 50 weather scenarios.

In order to identify the benefits that are brought by sources of flexibility such as storage, demand-response or advanced wind turbines, and by increasing the interconnection between European power systems, we explore three options that are presented below. The optimal portfolio of technologies is computed for each of the options. We then analyse the impacts in terms of investment and operational costs of each of the options.

3.4.1 Presentation of the options

As mentioned above, we have determined the optimal set of investments in flexibility solutions for three options. These options differ in terms of the set of technologies that are available:

- **Option (I)** – In the first option, the model is only allowed to invest in flexible thermal generation (including retrofitting). This option can reflect situations in which the regulatory framework does not allow other technologies such as demand-response, storage or interconnectors to participate in the provision of flexibility
- **Option (II)** – In the second option, the model has more technologies to combine: storage, demand-response and system-friendly RES are now available.
- **Option (III)** – In the third option, interconnectors are considered as a way to increase the flexibility of the European power system. This option will allow us to highlight the role of an increased level of cooperation between Member States.

		Option (I)	Option (II)	Option (III)
Optimised deployment	**Available flexibility solutions**	Gas-fired generation	Gas-fired generation **Demand-response** **Storage**	Gas-fired generation **Demand-response** **Storage** **Interconnectors**
	Available flexibility improvements	Coal retrofits Gas retrofits	Coal retrofits Gas retrofits **Advanced onshore wind**	Coal retrofits Gas retrofits **Advanced onshore wind**
Assumptions	**Based on METIS EUCO30**	Solar, wind, run-of-the-river, large hydro, biomass, waste, nuclear, coal and lignite capacities, fuel and CO_2 prices, annual demand		
	Other assumptions	Interconnectors (current network + currently under construction) Storage technologies (2015 capacities) Demand-response (2015 capacities)	Interconnectors (current network + currently under construction)	

Table 9 - Definition of the options

In Option (II) and Option (III), two flexibility solutions are assumed to be installed in all cases: load-shifting demand-response and system-friendly onshore wind turbines, given their very low investment costs.

3.4.2 Main indicators for the analysis of the options

Several indicators can be computed to analyse the modelling results. The following ones will be used in the next section to highlight the differences between the three portfolios of flexibility solutions corresponding to the three options described above.

- **Installed capacities and associated power generation -** These indicators (respectively measured in MW and MWh) corresponds to the capacity of the flexibility solutions that have been selected by the model and to their annual generation of electricity.
- **Investment costs -** This indicator (measured in M€ per year, expressed as annuities) corresponds to the cost of the optimal flexibility portfolio (excl. operational costs)
- **Production costs -** This indicator corresponds to the production and running costs associated to power generation and reserve procurement
- **Social welfare -** This indicator corresponds to the socio-economic welfare. It is given by the sum of the producer surplus, consumer surplus and congestion rents.
- **Provision of flexibility -** This indicator corresponds to the impact of each technology on the flexibility needs. The provision of flexibility of a given technology is calculated by comparing the flexibility needs based on the residual load (as explained in Section 2.2) to residual flexibility needs. The latter are based on the residual load minus the technology generation profile. In the detailed results presented in Annex B, we also present the contribution of a given technology to the residual flexibility needs after having taken into account the contribution of interconnectors. This is particularly useful for small countries where the dynamics of the flows on interconnectors are largely dominated by neighbouring countries.

Figure 26 illustrates the computation of the provision of flexibility by a given technology.

Step A – Compute the daily flexibility needs based on the ***residual load***

Step B – Compute the residual daily flexibility needs based on the ***residual load – technology X generation profile***

The difference between the two quantities is the contribution of technology X in the provision of flexibility

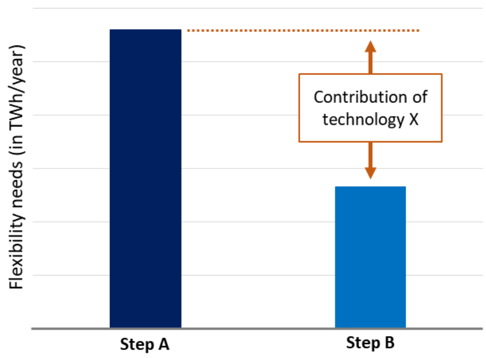

Figure 26 - Methodology to asset the contribution of a technology to flexibility needs

3.4.3 Main results at the European level

This section is devoted to the analysis of the optimal flexibility portfolios computed for each of the options and of their differences at the European level. All results are available at the Member State level, and can be found in Annex B. The following tables provide a high-level summary of the results for each of the three considered options.

Installed capacities

Table 10 presents the installed capacities per option at the EU28 level. By comparing Option (II) to Option (I), one can see that thanks to investments in storage and demand-response one can avoid retrofitting coal and gas units, and substantially decrease the investments in gas-fired generation by around 15 GW. The flexibility provided by storage and demand-response allow for a better exploitation of baseload and mid-merit resources, in particular thanks to their ability to reduce peak demand. Finally, in Option (III), investments in additional interconnection projects further reduce the need for gas-fired generation by 8 GW.

Technologies [GW]		Option (I)	Option (II)	Option (III)
Variable RES-e	Solar	238	238	238
	Wind[43]	331	228	228
	Run-of-the-river	50	50	50
Hydro storage	Lake + Mixed PHS	138	138	138
	Pure PHS	31	37	37
Batteries	*1-hour discharge time*	-	2	2
Demand response	*Load shedding*	-	4	4
	Load shifting	-	8	8
Interconnectors	*Import capacity*	181	181	205
Lignite		47	47	47
Waste		12	12	12
Biomass		42	42	42
Coal	Legacy	44	46	46
	Retrofit	2	0	0
	State-of-the-art	16	16	16
Nuclear		110	110	110
CCGT	Legacy	104	110	110
	Retrofit	9	3	4
	State-of-the-art	87	78	77
OCGT	Legacy	27	27	27
	State-of-the-art	34	26	18
Total installed capacities		1503	1403	1419

Table 10 - Installed capacities at the EU28 level per option.

[43] The installed capacity of wind power decreases in Option (II) and Option (III) because of the introduction of advanced wind turbines (which have an overall higher load factor). The capacities are fixed so that the annual wind energy generation remains

The installed capacities of the technologies shown in italic in Table 10 are the results of an optimisation exercise, which takes into account potentials at the Member State level for a number of technologies and for interconnectors. The results may significantly vary should the potential and costs assumptions change. We therefore recommend that Member State use their own potentials and corresponding costs when defining their optimal portfolio of flexibility solutions.

Generation

Table 11 presents the contribution of each technology in the provision of electricity at the EU28 level, for each of the considered options. In particular, one can note that RES-e, baseload and mid-merit technologies, are better exploited in Option (II) and Option (III). In the case at hand, the assumed gas, coal and CO_2 price result in a transfer from gas-fired generation to coal and lignite. The RES-e curtailments is also found to be reduced, while nuclear can be seen to be better exploited.

The flexibility introduced by solutions such as storage, demand-response and interconnectors allows the system to increase the number of full-load hours of baseload technologies and to avoid expensive start-up costs by displacing the consumption of electricity both in time (demand-response and storage) and space (interconnectors).

Technologies [TWh]		Option (I)	Option (II)	Option (III)
Variable RES-e	Solar	303	305	305
	Wind	688	690	691
	Run-of-the-river	168	168	168
Hydro storage	Lake + Mixed PHS	210	208	208
	Pure PHS	36	40	39
Batteries and DSR		-	3	3
Lignite		262	265	266
Waste		55	55	55
Biomass		10	8	8
Coal		340	357	367
Nuclear		789	796	803
CCGT		466	439	419
OCGT		3	2	2
Total generation		3330	3336	3334

Table 11 – Generation at the EU28 level by option

Costs and social welfare

Table 12 presents the main cost and welfare figures at the EU28 level for each of the considered options. Investment costs are found to moderately decrease when more flexibility solutions become available in Option (II) and Option (III). The bulk of the savings emerge from operational costs (electricity generation and procurement of

equal to the METIS EUCO30 value in all options (the wing generation figures shown in Table 11 slightly increase in Options (II) and (III) due to a reduction of curtailment).

reserves): up to 1.9 B€ of production costs (which cover both the provision of electricity and the procurement of reserves) can be saved in Option (III) compared to Option (I).

Indicator [M€/year]	Option (I)	Option (II)	Option (III)
Investment costs[44]	8 180	8 030	7 970
Investment savings	-	150	210
Production costs	71 200	70 000	69 300
Production savings	-	1 200	1 900
Welfare gains	-	1 800	2 600
Total benefits (investment savings and welfare gains)	-	1 950	2 810

Table 12 - Cost and welfare figures at the EU28 level per option

Overall, allowing the whole range of flexibility solutions to participate in the provision of flexibility results in an increase of the EU28 social welfare by up to 2.6 B€ per year in Option (III). When taking the investment savings into account, the total benefits are found to be of the order of 2.8 B€ per year in Option (III).

[44] One should note that the investment costs strongly depend on the assumed level of residual capacities in the gas sector (i.e. the currently existing gas-fired generation units that are assumed to remain operational in 2030).

1

Allowing storage, demand-response, system-friendly RES and interconnectors to participate in the provision of flexibility results in benefits of the order of 2.8 B€ per year at the EU28 level.

Investment costs

The results demonstrate that, when given the possibility, the model modifies the optimal portfolio of technologies and invests in storage, demand-response and interconnectors. The investment costs of these technologies, introduced in Option (II) and Option (III), are more than compensated for by the savings they induce in terms of investments in flexible thermal generation technologies. The investment annuities at the EU28 level in Option (II) are lower by 150 M€ than in Option (I) and by 200 M€ per year in Option (III).

Figure 27 illustrates the impact of both Option (II), on the left-hand side, and Option (III) on the right-hand side in terms of total costs at the EU28 level. In Option (II), investment costs of around 1 B€ per year in gas-fired units are avoided thanks to the introduction of storage (mostly PHS and batteries), and demand-response technologies. Unlocking the possibility to further expand the cooperation among Member States by increasing the interconnection capacity allows the system to avoid investment costs in gas-fired generation of around 1.4 B€ per year.

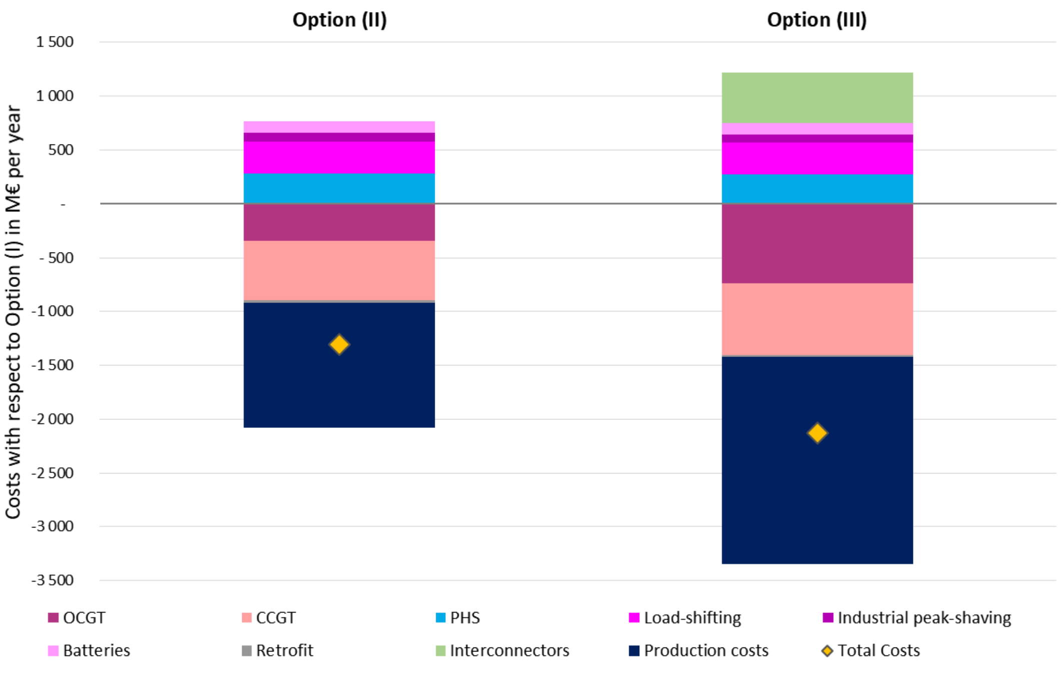

Figure 27 - Total costs compared to Option (I)

The introduction of further flexibility solutions in Option (II) allows to avoid investments of the order of 15 GW of gas units over EU28 (7 GW for OCGTs, 8 GW for CCGTs). The introduction of additional interconnectors in Option (III) allows to further reduce the capacity of flexible thermal generation technologies. The results indeed show that around 25 GW of gas-fired investments (15 GW for OCGTs, 10 GW for CCGTs) can be avoided in Option (III) compared to Option (I). In both Option (II) and Option (III), retrofitting thermal plant is also found to be less valuable: the cost of retrofitting 5 GW of CCGT units and around 2 GW of coal plants is avoided thanks to the introduction of demand-response and batteries which contribute to hourly flexibility needs at a lower cost than thermal plants.

In particular, the penetration of industrial demand-response (peak-shaving) in Option (II) and Option (III) can be seen to avoid investments in OCGTs. Figure 28 presents the total costs of peak shaving measures and OCGTs, depending on their average annual duration of use.

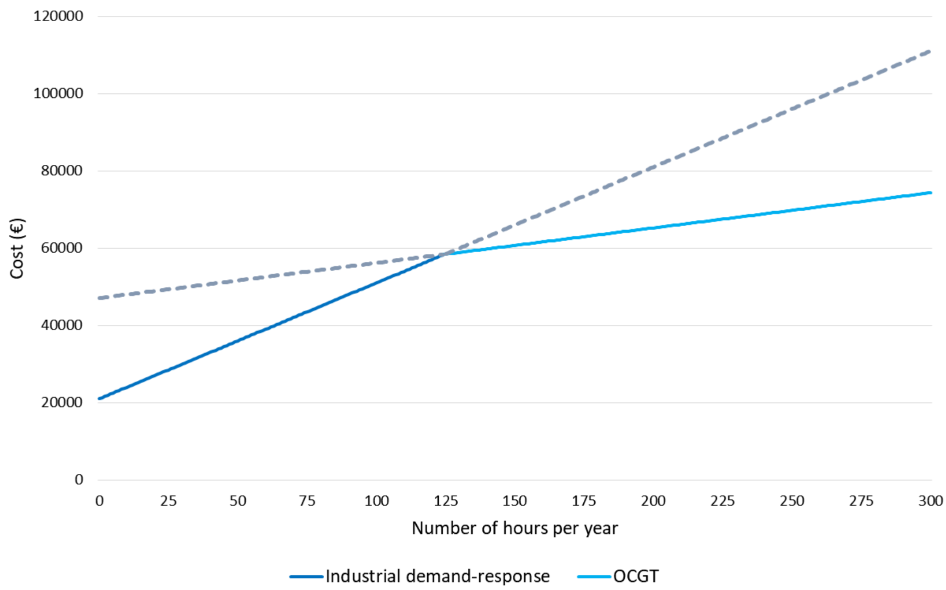

Figure 28 - Cost of industrial demand-response and OCGTs depending on the duration of use

Industrial demand-response is cheaper to install but more expensive to operate than OCGTs. However, if used less than 130 hours per year, industrial demand-response remains cheaper than OCGTs. As a consequence, all the gas-fired capacity that was used less than 130 hours per year in Option (I) is replaced by industrial demand-response in Option (II) and Option (III), provided the potential allows it.

Around 4.1 GW of industrial demand-response are installed in Option (II), representing around 60% of the EU28 potential. In Option (III), the further development of interconnectors mitigates the needs for this peak capacity, which results in a lower industrial demand-response penetration at the EU28 level (3.7 GW).

Production costs

More importantly, Option (II) and Option (III) both induce large savings in terms of production costs. Indeed, thanks to the extra flexibility introduced into the European electricity system in these options, RES-e, baseload and mid-merit technologies can be much better exploited than in Option (I).

As illustrated by Figure 29, gas units' production costs decrease significantly (more than 2 B€ per year in Option (II)). Indeed, thanks to the introduction of storage and demand-response, the demand peaks that have to be faced by conventional generation are lower in Option (II) and Option (III) than they were in Option (I). The use of peaking plants is reduced accordingly. Their production is compensated for by cheaper technologies such as nuclear power, coal- and lignite-fired units. In Option (II) and Option (III), the system is found to be flexible enough to better exploit RES-e, baseload and mid-merit technologies. The ability of the system to store excess generation, to delay consumption, or to share excess generation with neighbouring countries allows for a better utilisation of resources.

In terms of CO_2 emissions, Option (II) and Option (III) are both found to moderately increase the gross CO_2 emissions of the electricity sector, respectively by 0.7% and 0.9% compared to Option (I), due to the better exploitation of baseload and mid-merit fleets, which are often carbon-intensive technologies (e.g. coal, lignite).

If the exercise were to be repeated with a CO_2 price that induces a coal-to-gas switching, it is likely that coal and lignite would be taken offline most of the time, and that competition between CCGTs would increase at the European level. Such a scenario would probably result in a larger share of electricity generated by gas-fired units, and a decrease of CO_2 emissions.

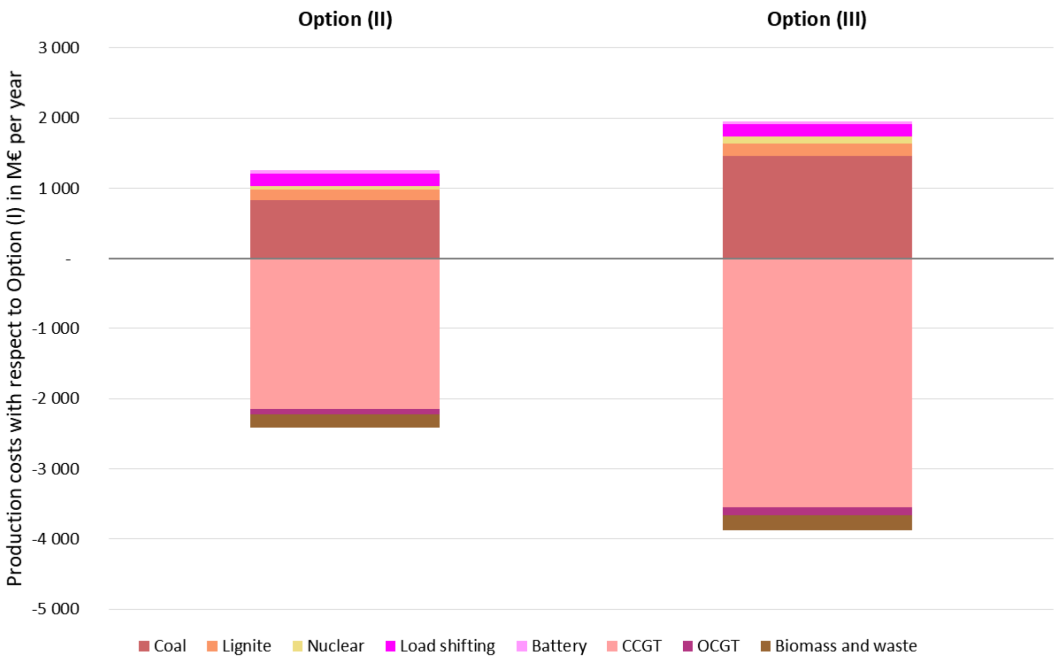

Figure 29 - Production costs compared to Option (I)

Overall, Option (II) induces savings of around 1.3 B€ per year compared to Option (I), of which more than 1.1 B€ are savings in terms of production costs. Option (III) induces around 2 B€ of savings compared to Option (II) at the EU28 level, of which 1.8 B€ correspond to savings in production costs.

The increase of social welfare is found to be larger than the reduction of production costs. This is driven by the following two effects: first, the lower investments costs in Option (II) and Option (III) allow to reduce the number of hours when demand cannot be met second, and second the geographical distribution of costs and welfare between the EU and the other modelled countries is found to be advantageous for the EU. Overall, as shown by Table 12, the total benefits are found to be up to 2.8 B€ per year.

2 Short-term demand-response and batteries can advantageously replace thermal units to provide electricity balancing reserves.

Short-term demand-response is found to play a great role in the provision of sub-hourly flexibility. Indeed, in Option (II) and Option (III), upwards synchronised reserves (FCR and aFRR) are mainly covered by hourly flexibility solutions: 7.7 GW of short-term demand-response and 2.1 GW of batteries at the EU28 level.

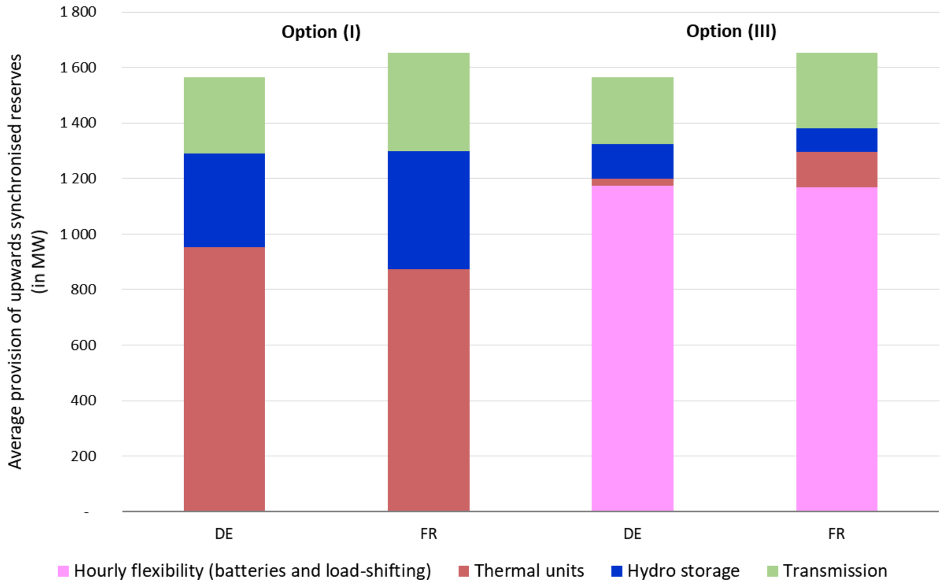

Figure 30 - Contribution of technologies to upwards synchronised reserve

As illustrated by Figure 30, France and Germany mainly use thermal units to meet the upwards synchronised reserve requirements in Option (I). The contribution of these technologies is found to be substantially reduced in Option (III). In these two countries, short-term demand-response covers almost all reserve needs that have to be covered at the national level[45]. However, in other Member States, short-term demand-response capacities cannot provide all the reserve needs, leading to the installation of batteries as a low-cost solution to provide reserves.

Figure 31 shows where batteries are installed in addition to short-term demand-response so as to cover sub-hourly flexibility needs. For example, in Finland and

[45] Our modelling assumes that reserves are dimensioned at the regional level. As a consequence, the total reserve needs are found to be lower than in a situation in which reserves are dimensioned at the national level. The model then has to find the optimal trade-off between a local provision of reserves and the reservation of interconnection capacity to allow for assistance between Member States to compensate for the fact that local reserves are lower than when dimensioned nationally. For more details, see COWI, "*Integration of electricity balancing markets and regional procurement of balancing reserves*", 2016 and Artelys, "*METIS Study S12 - Assessing Market Design Options in 2030*", 2016.

Sweden, batteries are installed so that the sum of load shifting and batteries reach the minimum local reserve demand. In other Member States such as France and Italy, there is no need for batteries as short-term demand-response exceeds the local reserve demand. Finally, in some countries, other existing solutions can provide sub-hourly flexibility, such as hydro storage in Spain, and are sufficient to avoid the installation of batteries.

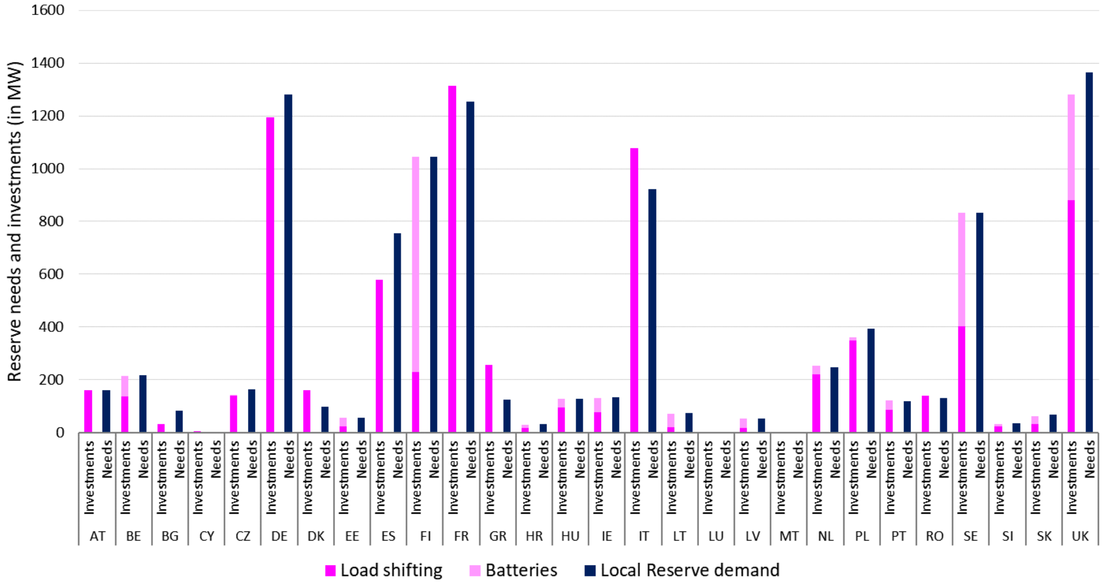

Figure 31 - Hourly flexibility investments compared to local balancing reserve needs

3 Low-cost PHS potentials can be exploited to cover a substantial share of the daily and weekly flexibility needs

While short-term demand-response and batteries have been shown to contribute to the provision of sub-hourly flexibility, PHS is found to cover a substantial share of both daily and weekly flexibility needs. The potential for low-cost PHS (with two existing reservoirs) is well exploited in Option (II). In Option (III), due to the additional flexibility brought by interconnectors, slightly less PHS capacity is installed in Spain, as illustrated by Figure 32.

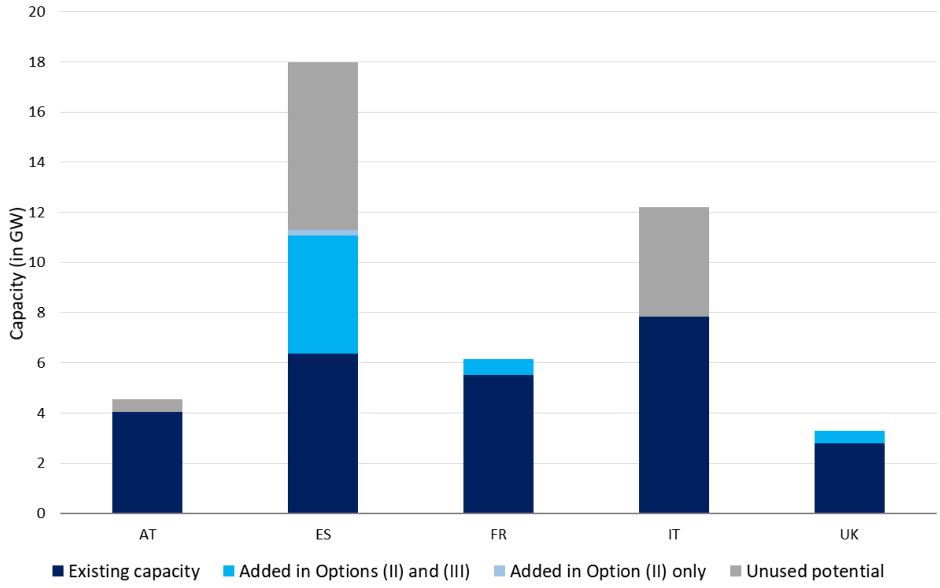

Figure 32 - Potential and installed capacity of PHS per option

PHS and other hydro assets are found to play a major role in the provision of daily and weekly flexibility, as is illustrated by Figure 33.

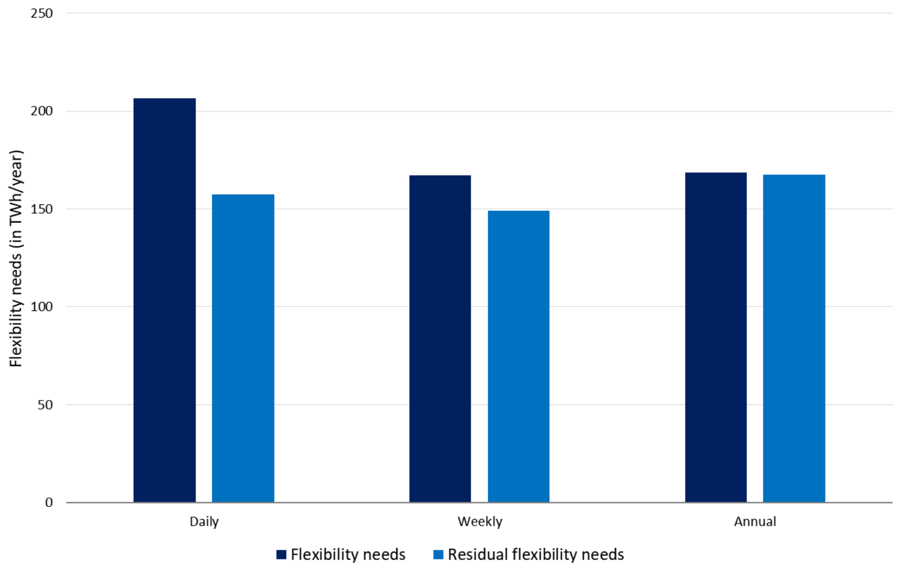

Figure 33 - Impact of hydro assets on flexibility needs at the EU28 level in Option (III)

Overall, at the EU28 level, hydro assets are found to cover 24% of the daily flexibility needs despite the fact that several countries cannot invest in additional PHS units due to the absence of potential. The contribution of hydro assets in the provision of daily flexibility reaches up to 51% of the daily needs in Spain. Hydro assets are also found to contribute to weekly flexibility needs: around 11% of the EU28 weekly needs are covered by these assets, and up to 32% in Sweden. However, hydro is shown to have a very moderate role in the provision of annual flexibility.

The high-cost PHS potential (i.e. with only one existing reservoir) is found not to be exploited in our modelling. Similarly, CAES are found not to be installed in any of the options. Two factors can explain the absence of investment in further storage facilities: first the investment costs of these two technologies are much more important than those of the low-cost PHS units, and second the small difference in production costs between coal- and gas-fired generation in this scenario (when the CO_2 price is taken into account) reduces the returns of arbitrage.

4 Adopting system-friendly wind turbines is found to significantly decrease the weekly flexibility needs at the European level

One of the flexibility solutions that we have considered is to install advanced onshore wind turbines with larger rotor-size-to-capacity ratios than conventional onshore wind turbines, allowing them to better capture low wind speeds. The capacity factor of advanced wind turbines displays a lower level of fluctuation, leading to an easier integration of these turbines in the power system.

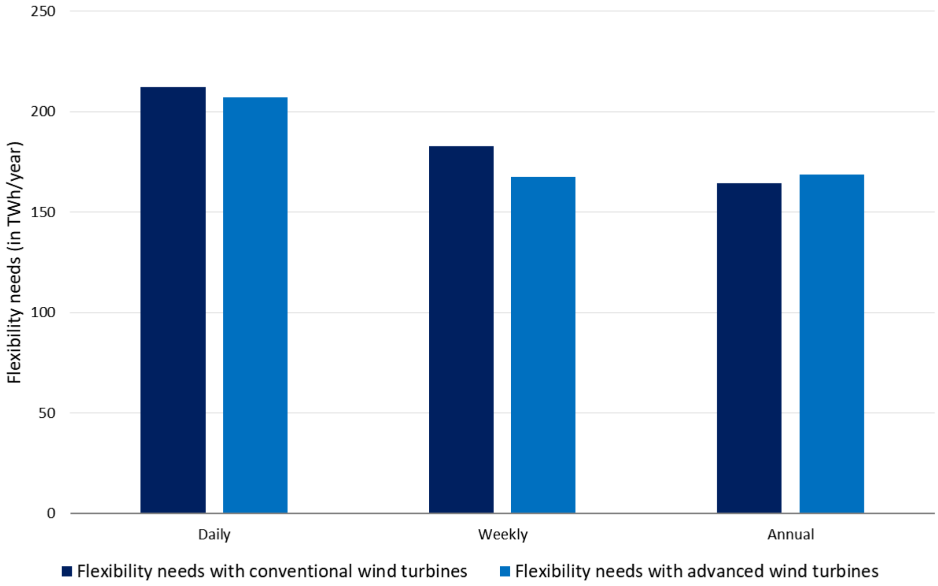

Figure 34: Flexibility needs in EU28 with classic and advanced wind turbines

If one were to only invest in advanced wind turbines, and to repower the existing ones, one would witness a decrease of weekly flexibility needs by 8% at the EU28 level (for the same total generation of electricity). Meanwhile, daily and annual flexibility needs remain quite stable with variations below 3%.

This observation is in line with the results presented in Section 3.2 which demonstrated that increasing the share of wind generation in demand has an impact on the weekly flexibility needs. The utilisation of advanced wind turbines instead of conventional ones is found to mitigate the increase of flexibility needs induced by the growing share of wind energy. This effect is therefore particularly visible in Member States with high wind shares, as shown by Figure 35.

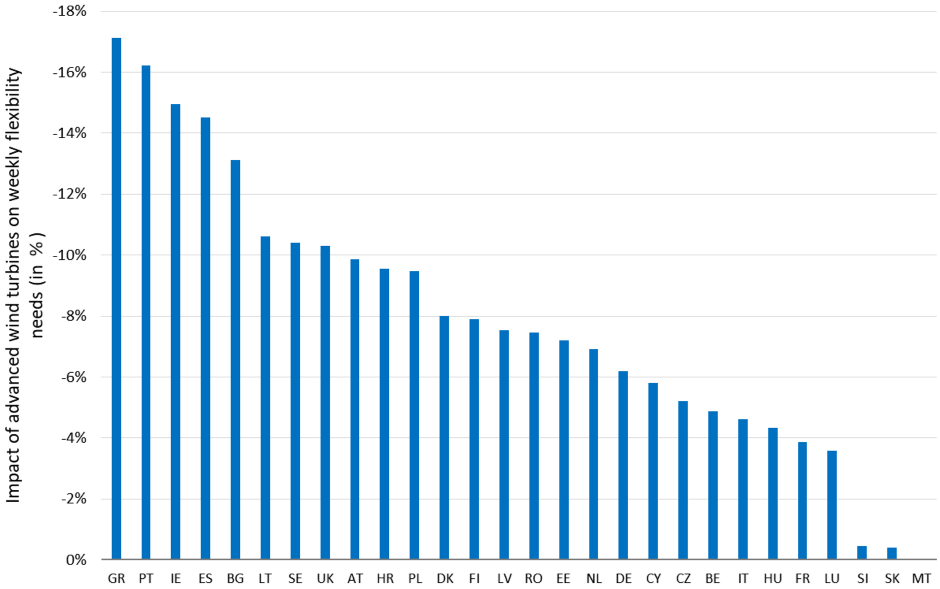

Figure 35 - Mitigation of weekly flexibility needs due to the use of advanced wind turbines

In Greece, Portugal, Ireland and Spain, wind generation represents more than 30% of the demand. Thus, the impact of using advanced wind turbines is significant: weekly flexibility needs decrease by more than 15% in these Member States. In contrast, the impact of using advanced wind turbines on the weekly flexibility needs is of course limited for Member States with very low wind shares (less than 7% in Luxembourg, Slovenia, Slovakia and Malta).

5 Interconnectors contribute significantly to the provision of daily and weekly flexibility

The existing and new interconnectors (see Figure 38) are found to have a positive impact on all types of flexibility needs, as illustrated by Figure 36, and to have a significant impact on daily and weekly flexibility needs.

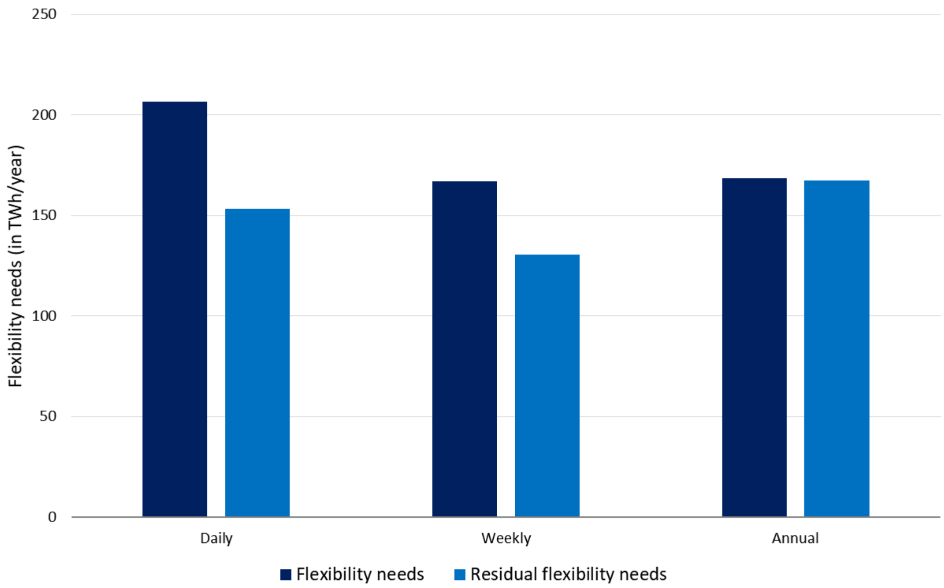

Figure 36 - Impact of transmissions on flexibility needs in EU28 in Option (III)

Overall, at the EU28 level, interconnectors provide around 26% of the daily flexibility needs and around 22% of the weekly flexibility needs, while annual flexibility needs are almost unaffected on average.

The situation can be quite different when looking at particular Member States. Indeed, when interconnectors provide flexibility to a Member State, they may degrade the flexibility situation in another Member State. To illustrate this point, the positive values in Figure 37 correspond to the contribution of interconnectors in the provision of flexibility in the countries where they are found to have a positive impact, while the negative values correspond to countries where they are found to increase flexibility needs. One can read that interconnectors are able to very well exploit the difference in demand profiles and RES-e generation at the daily and weekly levels and to reduce the needs that have to be covered by other technologies, but have almost no effect on the annual flexibility needs.

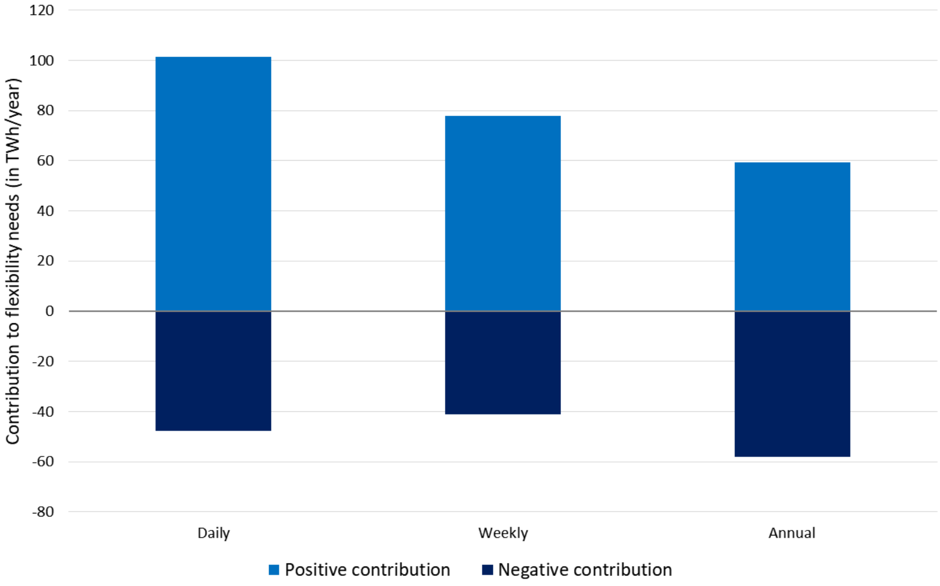

Figure 37 - Contribution of interconnectors to flexibility needs in EU28 in Option (III)

Figure 38 shows the interconnectors that are reinforced in Option (III). One should note that this list of investments should not be considered as the optimal set of interconnection investments since, by assumption, the model is only allowed to invest in a subset of the latest list of PCIs (PCIs with status "planning" or "permitting").

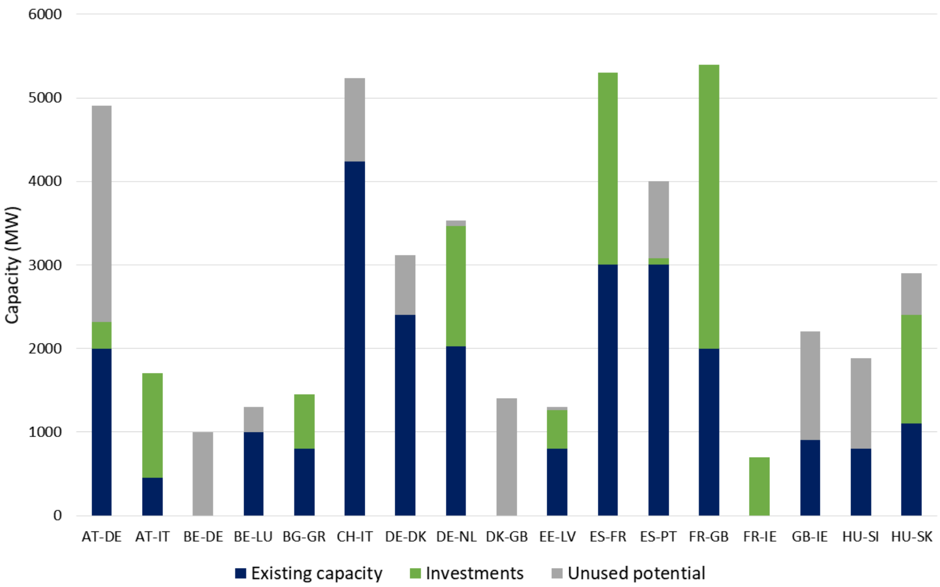

Figure 38 - Added transmission capacity in Option (III)

Around 12 GW of interconnection capacity are added to the system. This enables a better use of RES-e, baseload and mid-merit fleets and leads to considerable savings in production costs, as is illustrated above.

4 Conclusion

The framework introduced in this report aims to assist Member States when drafting their NECPs, and in particular the sections related to flexibility. We have proposed a three-step process to design flexibility portfolios that is illustrated in Figure 39.

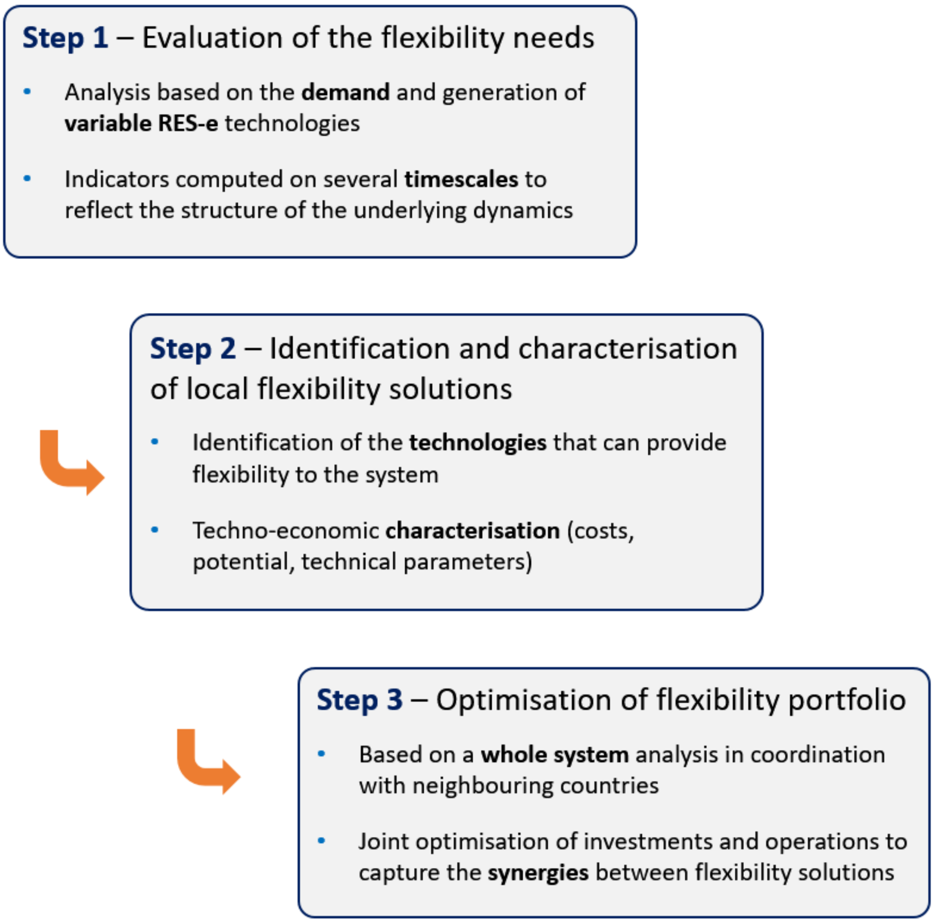

Figure 39 - Recommended framework to establish flexibility portfolios

First, the flexibility needs are evaluated, based on national RES-e ambitions and scenarios. A set of indicators evaluating flexibility needs is introduced in order to capture how the need for flexibility evolves on different timescales as the share of RES-e increases. Second, the local flexibility solutions are identified, in terms of potential, costs, and technical characteristics. Finally, we recommend to perform a whole system analysis at a regional level in order to define the flexibility portfolio that allows for the most cost-efficient integration of renewables by exploiting regional synergies.

An application of the methodology at the European level is presented. The key lessons that can be drawn from this exercise are:

- Flexibility needs strongly depend on the ambition in terms of RES-e deployment, but also on other characteristics of the local energy system: structure of the economy, presence of electric heating or air conditioning, etc.

- There is no "one-size-fits-all" solution to the flexibility challenge, as potential and costs associated to flexibility solutions such as demand-response, storage and interconnectors can vary from project to project, and from country to country.
- Important benefits can be generated by ensuring that flexibility solutions such as demand-response, storage and interconnectors can compete on a level playing field with thermal solutions. At the European level, the social welfare can be increased of up to 2.8 B€ annually with respect to a situation in which Member States would only invest in thermal units to meet their flexibility needs.

Finally, due to the interconnected nature of the electricity sector, Member States should be encouraged to share assumptions and methodologies to ensure their respective NECPs are compatible with one another and exploit potential regional synergies.

Annex A The METIS and Artelys Crystal Super Grid models

A.1 The METIS model

METIS is an on-going project initiated by DG ENER[46] for the development of an energy modelling software, with the aim to further support DG ENER'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 ENER.

METIS is an energy modelling software covering in high granularity (both in geographical space and time) the whole European power system and markets. METIS relies on the Artelys Crystal Super Grid platform. This platform provides a graphical user interface, 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 scenarios.

For the scope of this work, simulations adopted a Member State level spatial granularity and an hourly time resolution (8760 consecutive time-steps per year).

The uncertainties regarding the demand and RES 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.

METIS works complementary to long-term energy system models (like PRIMES from NTUA, POTEnCIA from JRC, etc.). For instance, METIS can provide results with an hourly time resolution on the impact of high shares of variable renewables or new investments in infrastructure, at the margin of scenarios provided by these long-term models. In the application of the methodology presented herein, the flexibility investments have been determined thanks to the Artelys Crystal Super Grid model, which is briefly presented in Annex A.2, while the annual demand and the other installed capacities are driven from the PRIMES EUCO30 scenario.

All the METIS Technical Notes are available on the DG ENER website dedicated to METIS[47], which also contains the METIS Studies, which present the analyses produced for the DG ENER policy experts to support their evidence-based policy making on themes such as market design, system adequacy, impact of PCIs, capacity remuneration mechanisms, etc. Recently, the power market module of METIS has also been exploited

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

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

to assess the benefits of several models of cross-zonal exchanges of balancing energy and of the regional procurement of balancing reserves[48].

Main characteristics of the power module

- **Calibrated scenarios –** METIS has been calibrated to a number of PRIMES scenarios. METIS versions of PRIMES scenarios include refinements on the time resolution (hourly) and unit representation (explicit modelling of reserve supply at cluster and MS level). Data provided by the PRIMES scenarios include: demand at MS-level, primary energy costs, fuel and CO_2 prices, installed capacities at MS-level, interconnection capacities. This work uses the 2030 METIS EUCO30 scenario, which is based on the 2030 PRIMES EUCO30 scenario. More details on the way PRIMES scenarios are integrated into METIS are available in the *METIS Technical Note T1 - Methodology for the integration of PRIMES scenarios into METIS*, which is available on the dedicated DG ENER webpage[47].
- **Geographical scope –** In addition to EU Member States, METIS scenarios incorporate ENTSO-E countries that are not part of the EU (Switzerland, Bosnia and Herzegovina, Serbia, former Yugoslav Republic of Macedonia, Montenegro and Norway) to model the impact of power exchanges with the EU power system, and the role of the flexibility solutions that can be deployed in these countries.
- **Reserve product definition –** METIS can simulate the procurement and activation of FCR, aFRR and mFRR reserves. The product characteristics for each reserve (activation time, separation between upward and downward offers, list of assets able to participate, etc.) are inputs to the model. In this study, we have taken the constraints of upwards synchronised reserves into account.
- **Reserve dimensioning –** The amount of reserves (FCR, aFRR, mFRR) that has to be secured by TSOs can be either defined by METIS users or be computed by the METIS stochasticity module. The stochasticity module can assess the required level of reserves that would ensure enough balancing resources are available under a given probability. Hence, METIS stochasticity module can take into account the statistical cancellation of imbalances between MS and the potential benefits of regional cooperation for reserve dimensioning.
- **Joint energy and reserve optimal dispatch** - METIS jointly optimises power generation and reserve procurement: the commitment of units is not only constrained by the power they have to generate to meet the demand, but also by the reserves they have to provide. Furthermore, in the application presented in this report, we have used a joint optimisation of investments, energy dispatch and reserve dispatch.

More details regarding the METIS power modules are provided in the METIS Technical Notes, in particular in *METIS Technical Note T5 - METIS Introduction And Architecture* and *METIS Technical Note T6 - Power System Module*, which are both available on the dedicated DG ENER webpage[47].

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[48] COWI, "*Integration of electricity balancing markets and regional procurement of balancing reserves*", 2016

A.2 Artelys Crystal Super Grid

Artelys Crystal Super Grid is a software solution developed and distributed by Artelys to generate and analyse prospective scenarios. It includes its own power and gas system models, based on public data.

Artelys Crystal Super Grid, based on a fundamentals model, jointly optimises the dispatch of generation to meet the energy and reserves demands, and investments to ensure that a given security of supply criterion is met. The software has the ability to simulate several energy vectors and their interactions: electricity, gas, heat and other resources (e.g. water, hydrogen, etc.) can be included in the modelling so as to identify synergies between these sectors.

The refinement of the modelling can be adapted to the situation at hand. In particular, the description of generation technologies can be set at the fleet level (all similar units are grouped into a single asset), the cluster level (allowing to take into account start-up costs and the reserve procurement constraints), or the unit level. Similarly, the description of the network constraints can be based either on the net transfer capacity (NTCs) between countries or bidding zones, or on an approximation of an AC optimal power flow (DC linear optimal power flow). In this study, we have worked at the cluster level, with an NTC-based power flow.

Artelys Crystal Super Grid includes a library of assets (generation technologies, storage technologies, demand-response technologies, interconnectors, etc.). The value of each parameter can be accessed and modified either through the graphical user interface or via the import/export features.

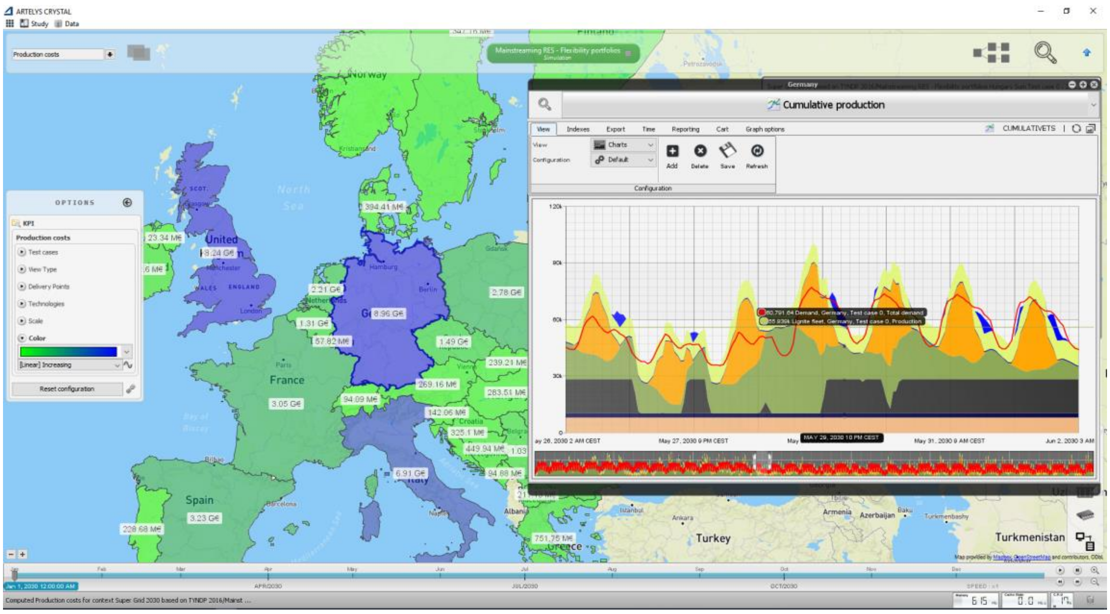

Figure 40 - Artelys Crystal Super Grid

Thanks to innovative decomposition techniques, Artelys Crystal Super Grid has been exploited in this study to optimise the portfolio of investments in flexibility solutions in

34 countries, using an hourly time resolution on the entire year over 50 annual weather scenarios (8760 time-steps per weather scenario)[49].

Artelys Crystal Super Grid is a tool that combines a sophisticated description of the energy system with an intuitive graphical user interface, which allows analysts and decision-makers to visualise and analyse results through a library of indicators ranging from techno-economic parameters (e.g. installed capacities, production costs, marginal costs, loss of load expectation, flexibility needs, congestion rents, etc.) to socio-economics and environmental indicators (consumer and producer surpluses, CO_2 emissions, etc.).

Artelys Crystal Super Grid is regularly used, including by academics, to evaluate the impacts of infrastructure projects (e.g. interconnectors) in terms of welfare, to analyse the impacts of policy measures, to conduct cost-benefit analyses, or to find the optimal set of investments to ensure that a given security of supply constraint is met and/or that a given decarbonisation target is reached.

[49] The optimisation problem contains over 250 investment decision variables, 500 million operational decision variables, and 450 million constraints. The problem is solved by Artelys Crystal Super Grid in around 6 hours on a high performance computing infrastructure.

Annex B Results at Member State level

This section presents the detailed results of the application of the recommended methodology at the Member State level. The optimal portfolios of flexibility options have been determined by an optimisation of the European social welfare. We have not taken into account the potential redistribution of costs and benefits between Member States. The congestion rents of interconnectors are assumed to be equally shared (50:50) between the connected countries.

The following sections contain:

Assumptions of the METIS EUCO30 scenario

- Electricity demand and variable RES-e generation
- Baseload and mid-merit thermal capacities

Results

- Step 1 results: Trajectory of flexibility needs over the 2020-2030 period
- Step 2 results: Potentials for a range of flexibility solutions[50]
- Step 3 results: Optimal portfolio of flexibility solutions per option[51]

In particular, in the presentation of the results of Step 3, we include a graph illustrating the contribution of each of the flexibility solutions in the provision of flexibility for Option (III). An example is provided below on Figure 41.

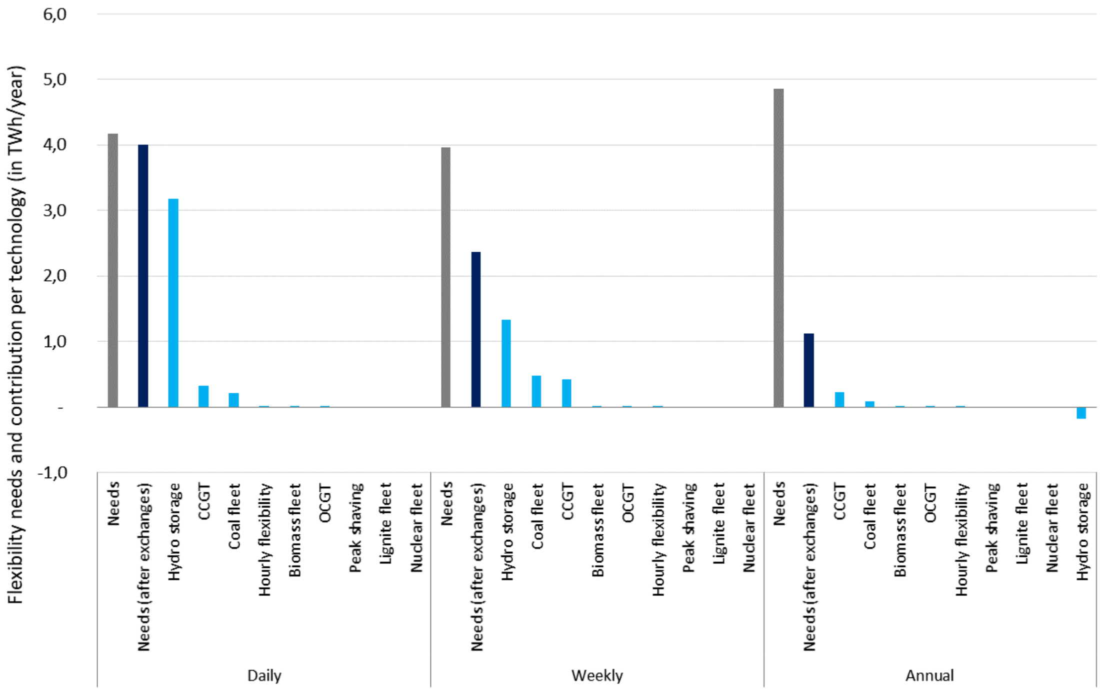

Figure 41 - Contribution of the flexibility solutions (example)

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[50] The costs can be found in Section 3.3.

[51] The options are described in Section 3.4.1.

On this figure, the bars denoted “Needs” correspond to the flexibility needs, and are computed using the methodology recommended in Section 2.2. In contrast with the figures of Section 3.2, the flexibility needs shown in this section take into account the contribution of advanced wind turbines.

The bars denoted “Needs (after exchanges)” correspond to the residual needs after the interconnectors have been taken into account: they correspond to the flexibility needs that have to be met with the country’s local resources (generation, storage, and demand-response). The difference between the two correspond to the contribution of interconnectors in the provision of flexibility. One should note that this contribution can be negative in some cases, for example when the dynamics of the energy flows are dominated by regional phenomena (e.g. large transit of energy through a small country or provision of flexibility to a neighbouring country).

Finally, the blue bars indicate the contribution of each of the technologies in the provision of the residual flexibility needs.

General remarks on the Member State level flexibility portfolios

The flexibility portfolios that are presented for each of the Member States in the following sections have been obtained through an optimisation aiming at maximising the European social welfare. When computing the optimal set of investments at the European level, the model is limited by the potential of each flexibility solution at the Member State level (in particular for PHS, CAES, demand-response, and interconnectors).

As a result, some investments may be driven by flexibility needs of neighbouring countries: it is possible that a given Member State is found to invest in a project (e.g. a storage facility) that is not strictly necessary from a local point of view, but that is found to be beneficial to some of its neighbours and that, therefore, contributes to increasing the European social welfare. Member States are encouraged to consult with their neighbours when defining their flexibility portfolios, so as to identify potential synergies.

In the results presented herein, the investment costs (including those that are in the common interest of several Member States) are therefore not attributed to a given Member State.

Finally, we would like to stress that the results presented in the following sections can significantly depend on the assumptions (in particular, the costs and potentials of flexibility solutions) and should therefore be understood as being illustrative of the methodology and not definitive results. Member States are encouraged to repeat the exercise with their own assumptions and scenarios.

B.1 Austria

Scenario description and flexibility needs

The following tables provide information related to the assumptions inherited from the PRIMES EUCO30 scenario.

	EUCO30
Power demand (in TWh/y)	77.2
Variable RES generation (in TWh/y)	20.4
of which wind onshore	*13.1*
of which wind offshore	*0.0*
of which PV	*7.3*

Table 13 - Demand and variable RES generation

Baseload and mid-merit capacities	EUCO30
Nuclear (in GW)	0.00
Coal (in GW)	0.78
Lignite (in GW)	0.00

Table 14 - Baseload and mid-merit capacities

The following graph presents the trajectory of flexibility needs over the 2020-2030 period.

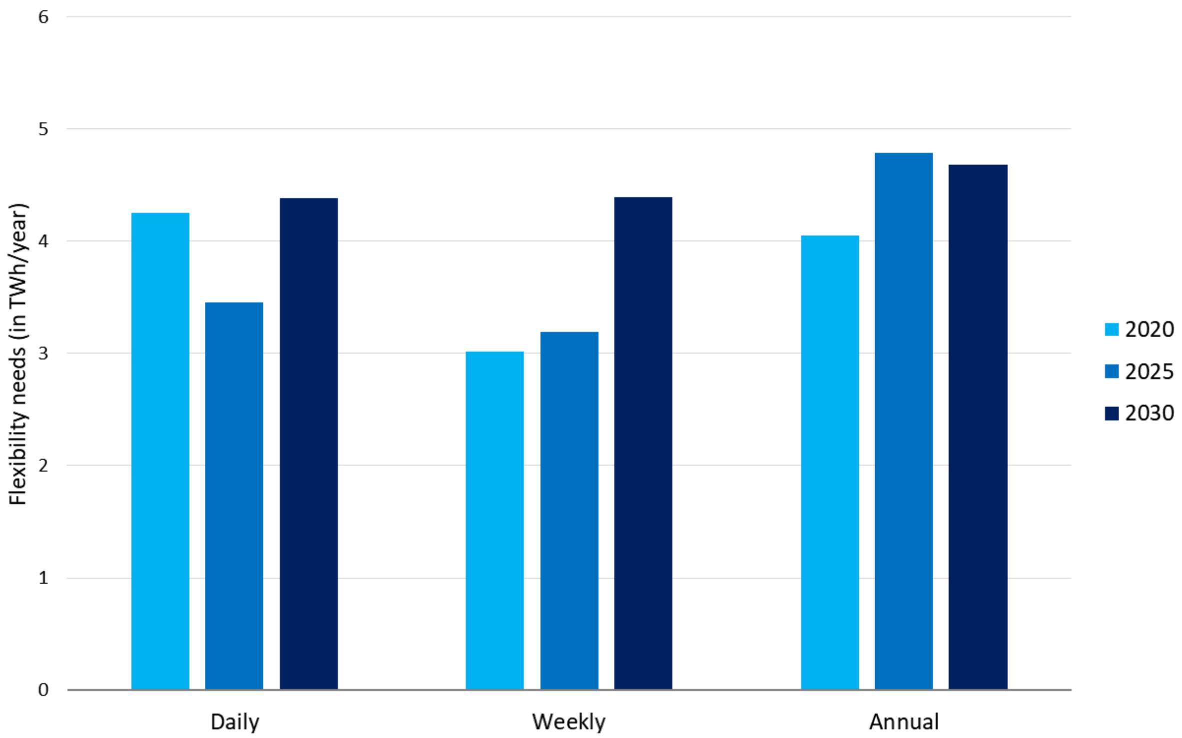

Figure 42 - Flexibility needs for 2020, 2025 and 2030

Flexibility portfolio

The following graph presents the potential for demand-response, storage and interconnectors, and the way these potentials are exploited in Options (II) and (III). Moreover, no batteries are found to be installed.

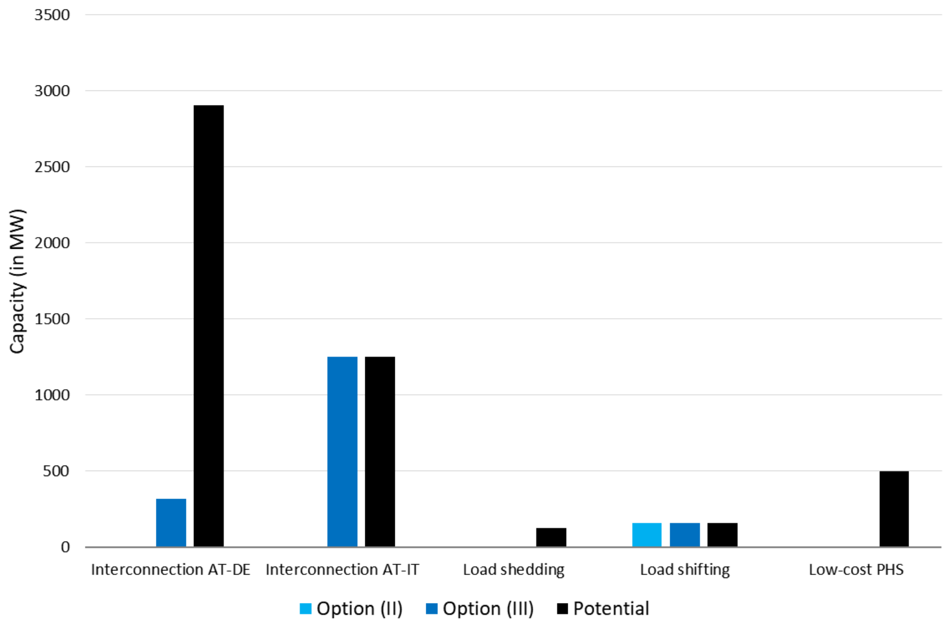

Figure 43 - Potential for flexibility solutions and installed capacities in Options (II) and (III)

Provision of flexibility

The following graph shows the contribution of each technology in the provision of daily, weekly and annual flexibility needs in Option (III).

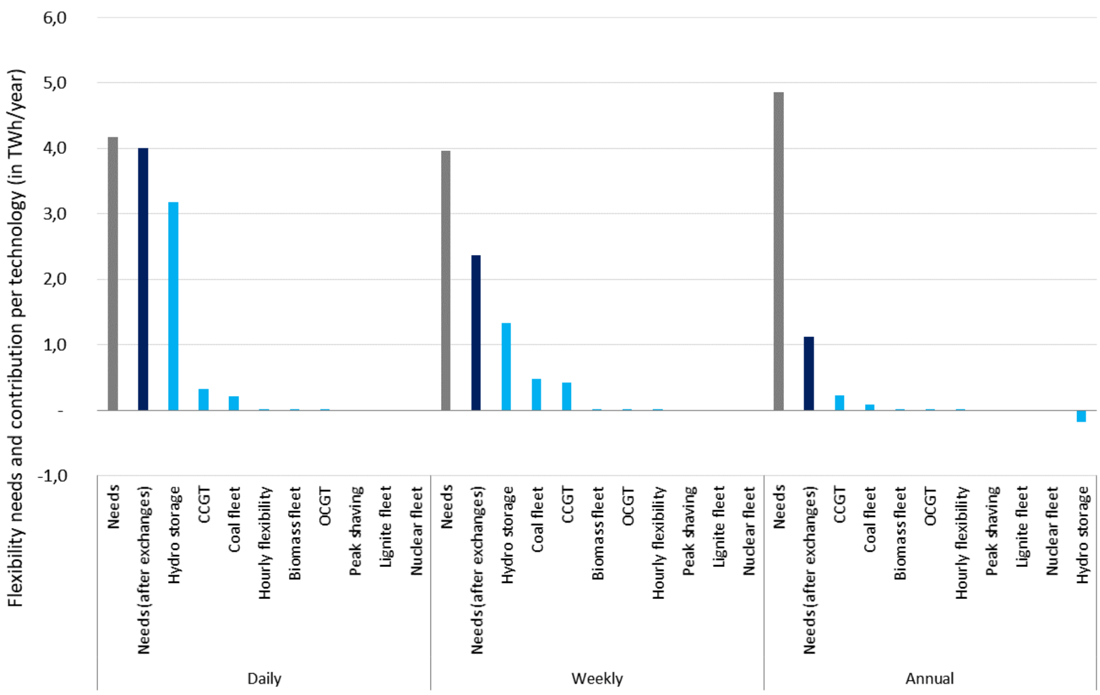

Figure 44 – Flexibility needs and provision of flexibility per technology in Option (III)

Finally, the following graph shows the contribution of each technology to sub-hourly flexibility needs (i.e. participation in reserve procurement) in Option (III).

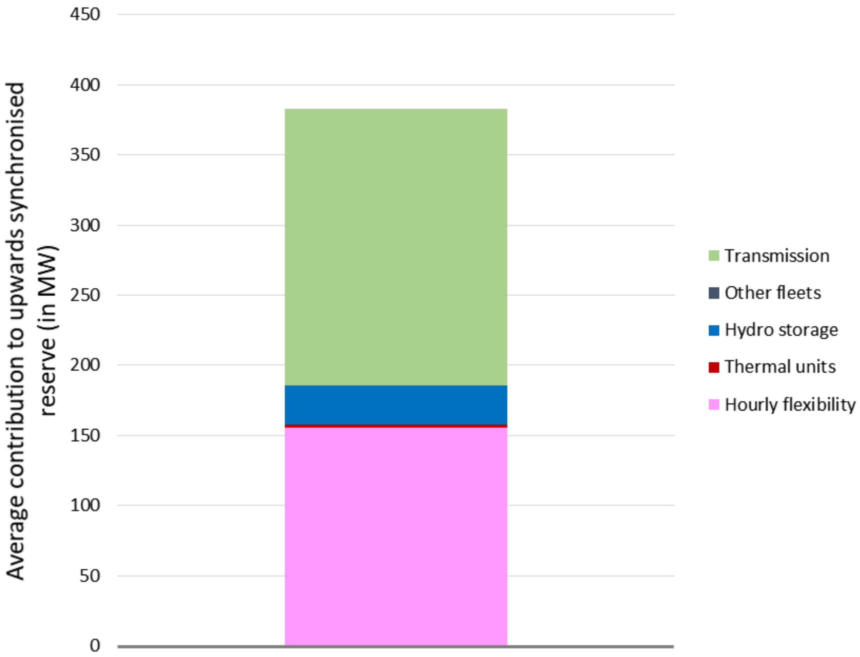

Figure 45 - Contribution to upward synchronised reserve

Social welfare

The following table shows the evolution of the national social welfare between Option (II) and Option (I), and between Option (III) and Option (I), expressed in M€ per year.

The social welfare is defined as the sum of the producer surplus (driven by the difference between the market price and the variable generation cost), the consumer surplus (driven by the difference between what consumers would be ready to pay for electricity and the market price) and half the congestion rents (the revenues captured by interconnectors by exploiting the price difference between two zones).

The figures below do not take into account the savings in terms of investment costs, as these savings could be split between all the countries that have a common interest in a given project. At the EU28 level, compared to Option (I), these savings correspond to 150 M€ in Option (II) and to 210 M€ in Option (III).

	Evolution of social welfare (in M€ per year)
From Option (I) to Option (II)	+ 35 M€/y
From Option (I) to Option (III)	+ 77 M€/y

Table 15 - Evolution of social welfare

B.2 Belgium

Scenario description and flexibility needs

The following tables provide information related to the assumptions inherited from the PRIMES EUCO30 scenario.

	EUCO30
Power demand (in TWh/y)	96.0
Variable RES generation (in TWh/y)	27.7
of which wind onshore	*9.4*
of which wind offshore	*11.0*
of which PV	*7.3*

Table 16 - Demand and variable RES-e generation

Baseload and mid-merit capacities	EUCO30
Nuclear (in GW)	0.00
Coal (in GW)	0.02
Lignite (in GW)	0.00

Table 17 - Baseload and mid-merit capacities

The following graph presents the trajectory of flexibility needs over the 2020-2030 period.

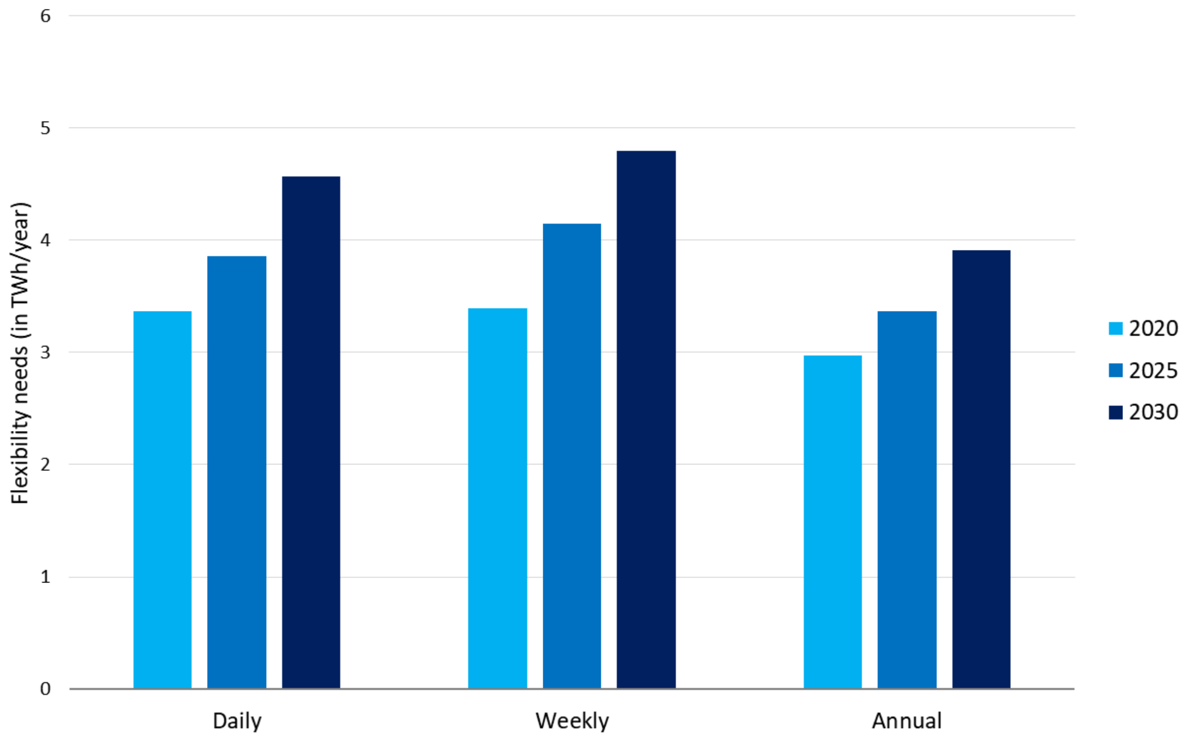

Figure 46 - Flexibility needs for 2020, 2025 and 2030

Flexibility portfolio

The following graph presents the potential for demand-response, storage and interconnectors, and the way these potentials are exploited in Options (II) and (III). Moreover, 70 MW of batteries are found to be installed in Option (II) and 80 MW in Option (III).

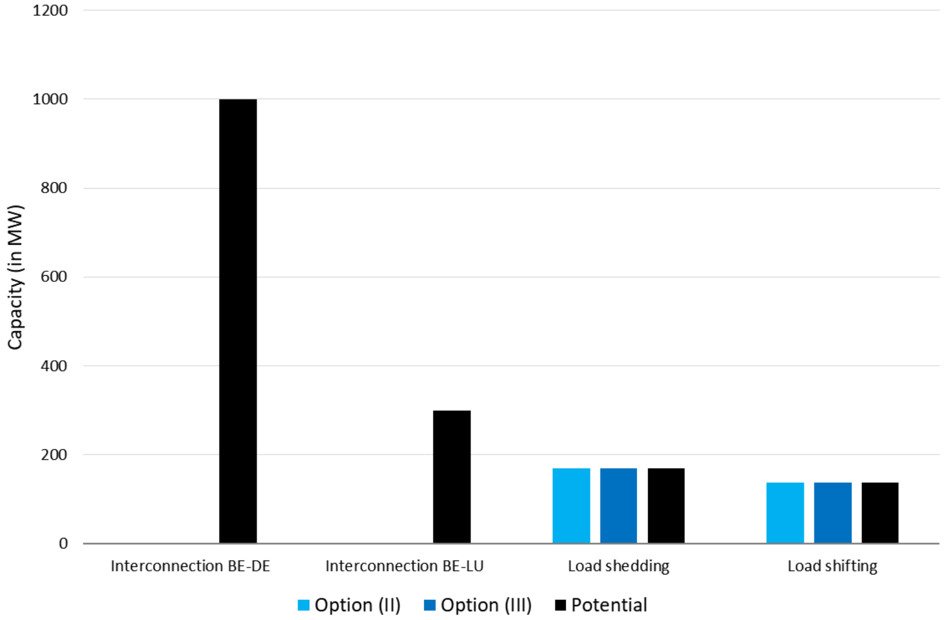

Figure 47 - Potential for flexibility solutions and installed capacities in Options (II) and (III)

Provision of flexibility

The following graph shows the contribution of each technology in the provision of daily, weekly and annual flexibility needs in Option (III).

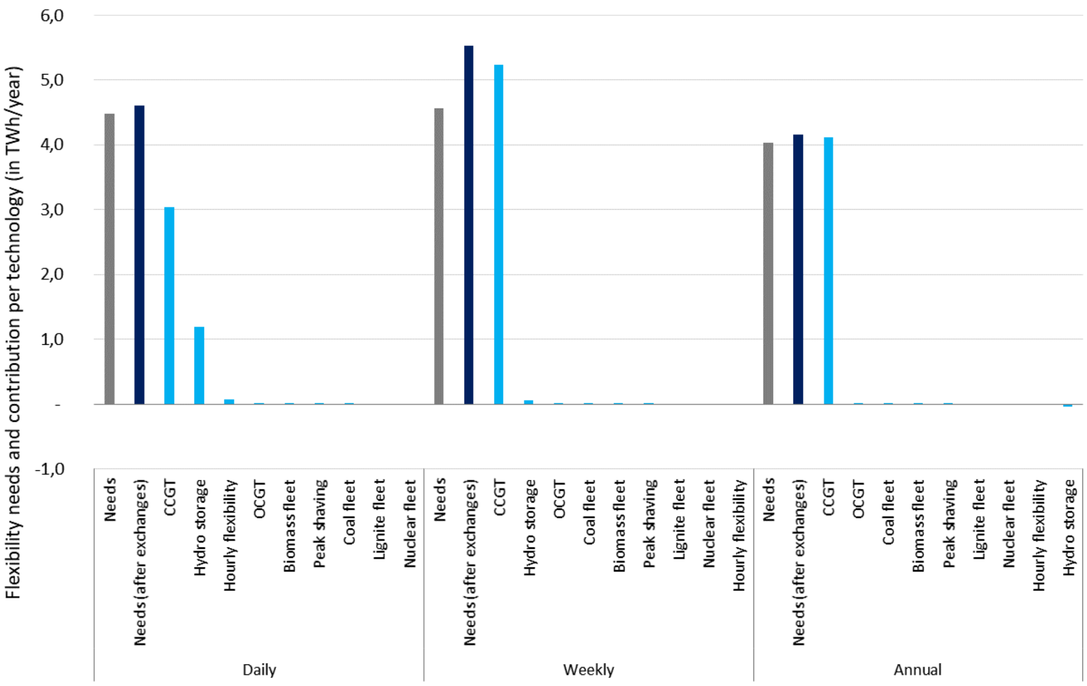

Figure 48: Contribution to flexibility needs per technology in Option (III)

The following graph shows the contribution of each technology to sub-hourly flexibility needs (i.e. participation in reserve procurement) in Option (III).

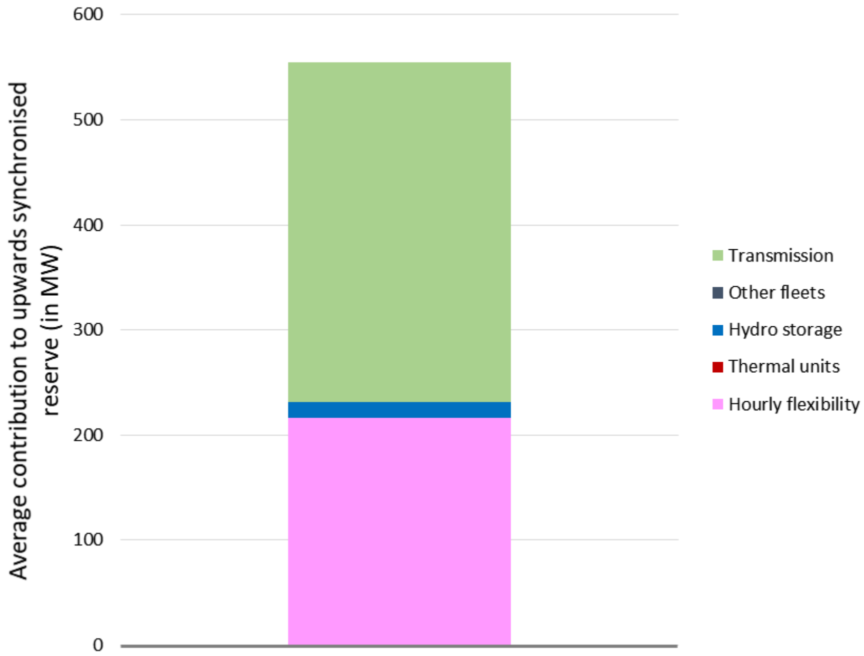

Figure 49: Contribution to upward synchronised reserve

Social welfare

The following table shows the evolution of the national social welfare between Option (II) and Option (I), and between Option (III) and Option (I), expressed in M€ per year.

The social welfare is defined as the sum of the producer surplus (driven by the difference between the market price and the variable generation cost), the consumer surplus (driven by the difference between what consumers would be ready to pay for electricity and the market price) and half the congestion rents (the revenues captured by interconnectors by exploiting the price difference between two zones).

The figures below do not take into account the savings in terms of investment costs, as these savings could be split between all the countries that have a common interest in a given project. At the EU28 level, compared to Option (I), these savings correspond to 150 M€ in Option (II) and to 210 M€ in Option (III).

	Evolution of social welfare (in M€ per year)
From Option (I) to Option (II)	+ 11 M€/y
From Option (I) to Option (III)	- 95 M€/y

Table 18 - Evolution of social welfare

B.3 Bulgaria

Scenario description and flexibility needs

The following tables provide information related to the assumptions inherited from the PRIMES EUCO30 scenario.

	EUCO30
Power demand (in TWh/y)	33.8
Variable RES generation (in TWh/y)	11.5
of which wind onshore	*7.5*
of which wind offshore	*0.0*
of which PV	*4.0*

Table 19 - Demand and variable RES generation

Baseload and mid-merit capacities	EUCO30
Nuclear (in GW)	1.92
Coal (in GW)	1.01
Lignite (in GW)	2.37

Table 20 - Baseload and mid-merit capacities

The following graph presents the trajectory of flexibility needs over the 2020-2030 period.

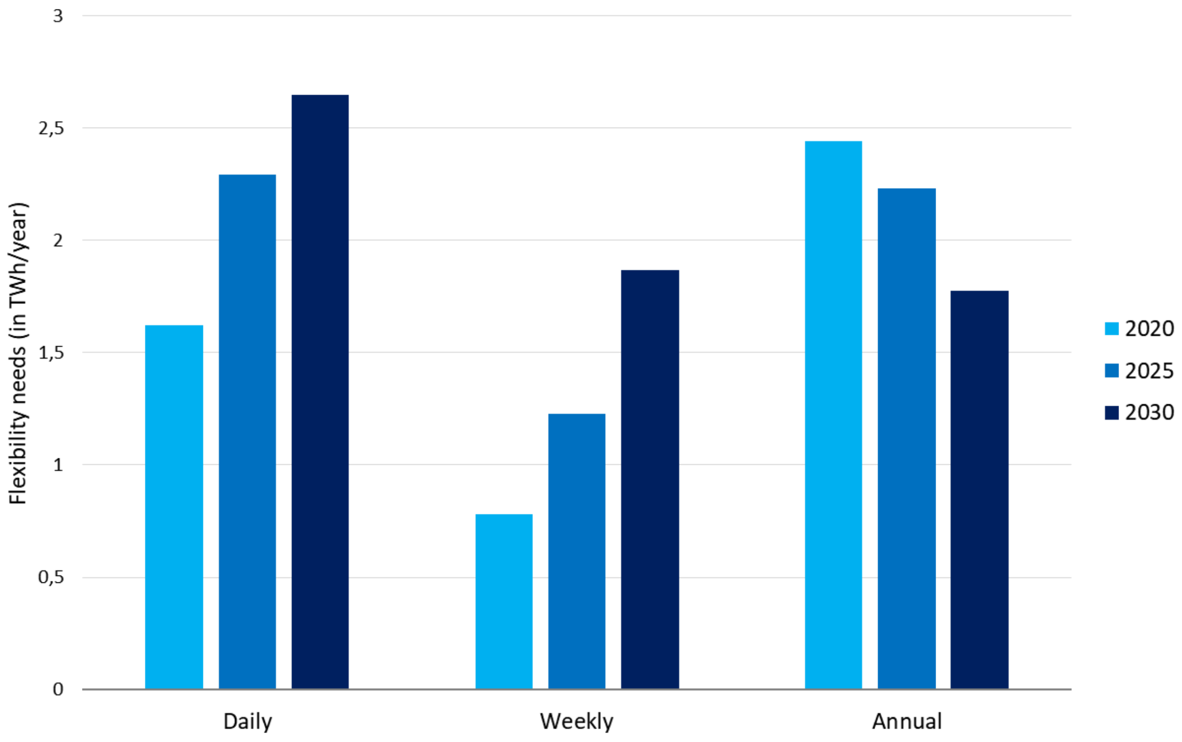

Figure 50 - Flexibility needs for 2020, 2025 and 2030

Flexibility portfolio

The following graph presents the potential for demand-response, storage and interconnectors, and the way these potentials are exploited in Options (II) and (III). Moreover, no batteries are found to be installed.

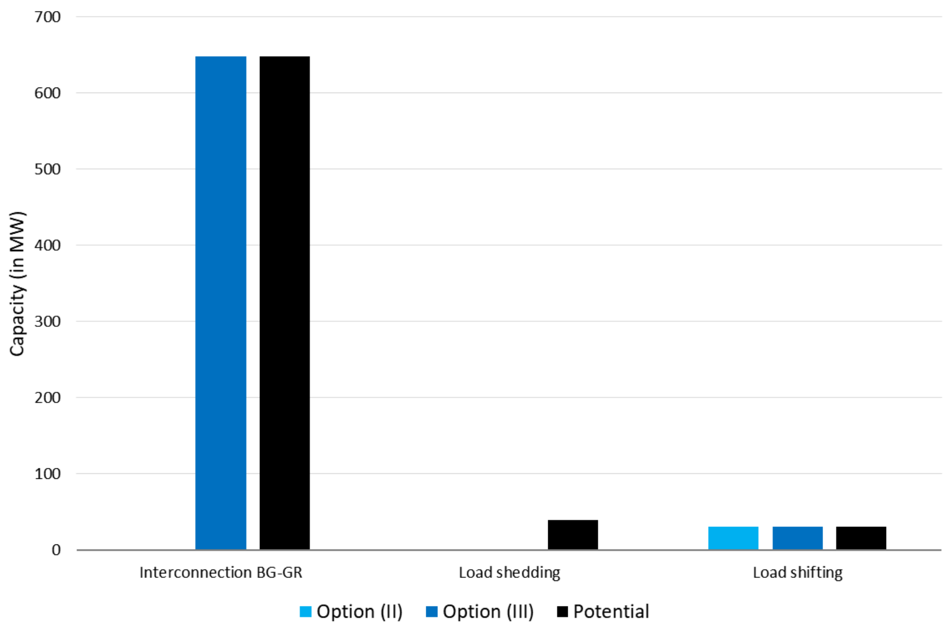

Figure 51 - Potential for flexibility solutions and installed capacities in Options (II) and (III)

Provision of flexibility

The following graph shows the contribution of each technology in the provision of daily, weekly and annual flexibility needs in Option (III).

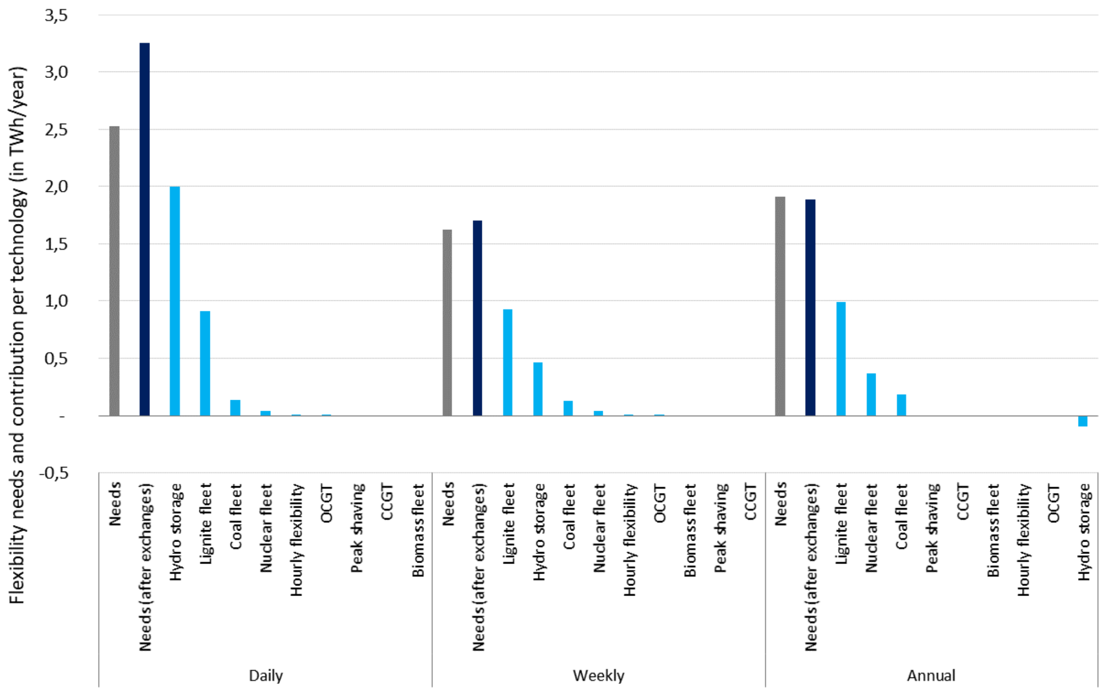

Figure 52 - Contribution to flexibility needs per technology in Option (III)

The following graph shows the contribution of each technology to sub-hourly flexibility needs (i.e. participation in reserve procurement) in Option (III).

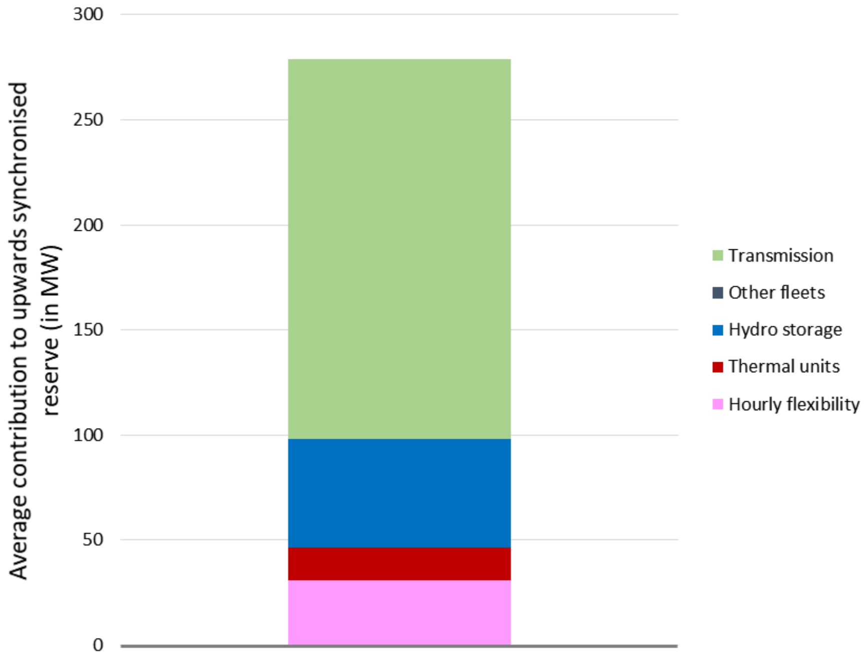

Figure 53: Contribution to upward synchronised reserve

Social welfare

The following table shows the evolution of the national social welfare between Option (II) and Option (I), and between Option (III) and Option (I), expressed in M€ per year.

The social welfare is defined as the sum of the producer surplus (driven by the difference between the market price and the variable generation cost), the consumer surplus (driven by the difference between what consumers would be ready to pay for electricity and the market price) and half the congestion rents (the revenues captured by interconnectors by exploiting the price difference between two zones).

The figures below do not take into account the savings in terms of investment costs, as these savings could be split between all the countries that have a common interest in a given project. At the EU28 level, compared to Option (I), these savings correspond to 150 M€ in Option (II) and to 210 M€ in Option (III).

	Evolution of social welfare (in M€ per year)
From Option (I) to Option (II)	- 16 M€/y
From Option (I) to Option (III)	- 2 M€/y

Table 21 - Evolution of social welfare

B.4 Croatia

Scenario description and flexibility needs

The following tables provide information related to the assumptions inherited from the PRIMES EUCO30 scenario.

	EUCO30
Power demand (in TWh/y)	18.2
Variable RES generation (in TWh/y)	4.2
of which wind onshore	*2.2*
of which wind offshore	*0.0*
of which PV	*2.1*

Table 22 - Demand and variable RES generation

Baseload and mid-merit capacities	EUCO30
Nuclear (in GW)	0.00
Coal (in GW)	0.65
Lignite (in GW)	0.00

Table 23 - Baseload and mid-merit capacities

The following graph presents the trajectory of flexibility needs over the 2020-2030 period.

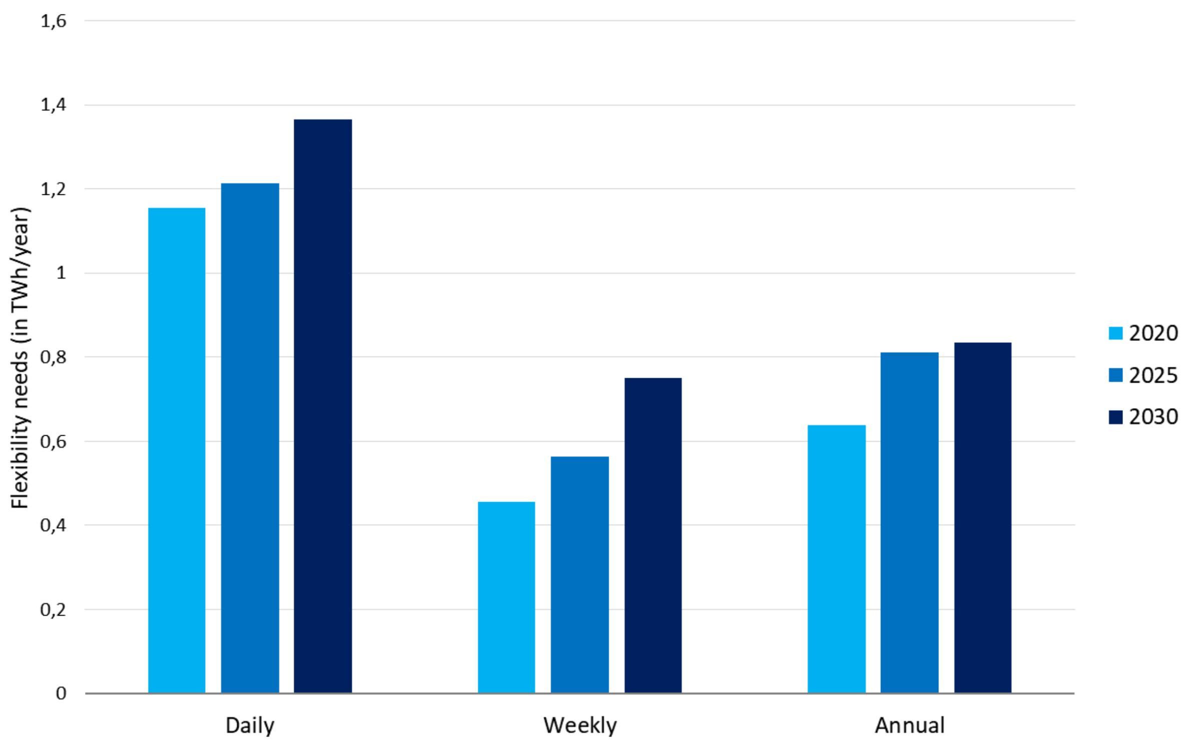

Figure 54 - Flexibility needs for 2020, 2025 and 2030

Flexibility portfolio

The following graph presents the potential for demand-response, storage and interconnectors, and the way these potentials are exploited in Options (II) and (III). Moreover, 10 MW of batteries are found to be installed in both Options (II) and (III).

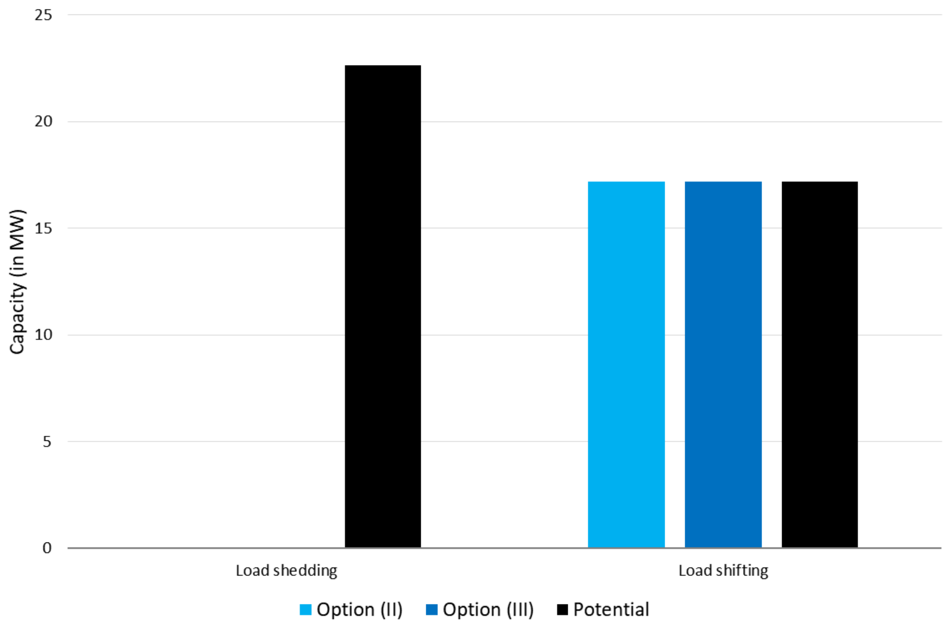

Figure 55 - Potential for flexibility solutions and installed capacities in Options (II) and (III)

Provision of flexibility

The following graph shows the contribution of each technology in the provision of daily, weekly and annual flexibility needs in Option (III).

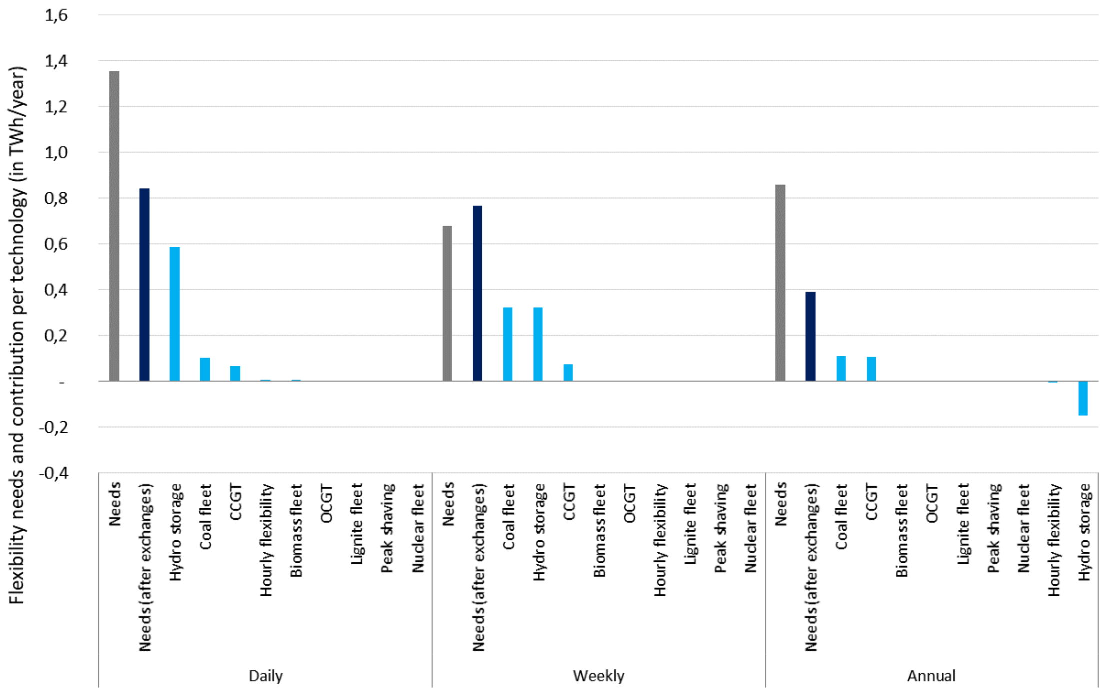

Figure 56: Contribution to flexibility needs per technology in Option (III)

The following graph shows the contribution of each technology to sub-hourly flexibility needs (i.e. participation in reserve procurement) in Option (III).

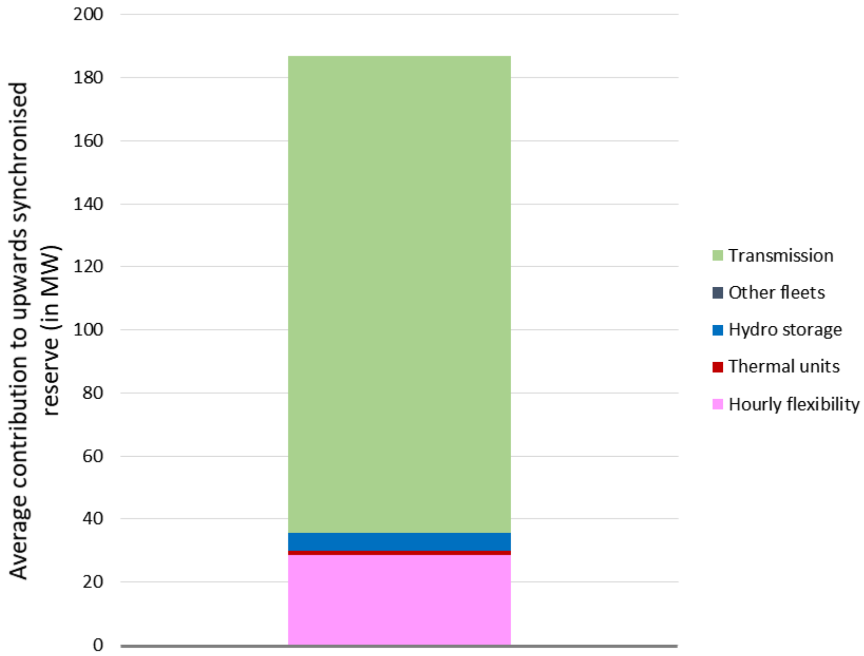

Figure 57: Contribution to upward synchronised reserve

Social welfare

The following table shows the evolution of the national social welfare between Option (II) and Option (I), and between Option (III) and Option (I), expressed in M€ per year.

The social welfare is defined as the sum of the producer surplus (driven by the difference between the market price and the variable generation cost), the consumer surplus (driven by the difference between what consumers would be ready to pay for electricity and the market price) and half the congestion rents (the revenues captured by interconnectors by exploiting the price difference between two zones).

The figures below do not take into account the savings in terms of investment costs, as these savings could be split between all the countries that have a common interest in a given project. At the EU28 level, compared to Option (I), these savings correspond to 150 M€ in Option (II) and to 210 M€ in Option (III).

	Evolution of social welfare (in M€ per year)
From Option (I) to Option (II)	+ 3 M€/y
From Option (I) to Option (III)	+ 4 M€/y

Table 24 - Evolution of social welfare

B.5 Cyprus

Scenario description and flexibility needs

The following tables provide information related to the assumptions inherited from the PRIMES EUCO30 scenario.

	EUCO30
Power demand (in TWh/y)	4.9
Variable RES generation (in TWh/y)	1.4
of which wind onshore	*0.5*
of which wind offshore	*0.0*
of which PV	*1.0*

Table 25 - Demand and variable RES generation

Baseload and mid-merit capacities	EUCO30
Nuclear (in GW)	0.00
Coal (in GW)	0.00
Lignite (in GW)	0.00

Table 26 - Baseload and mid-merit capacities

The following graph presents the trajectory of flexibility needs over the 2020-2030 period.

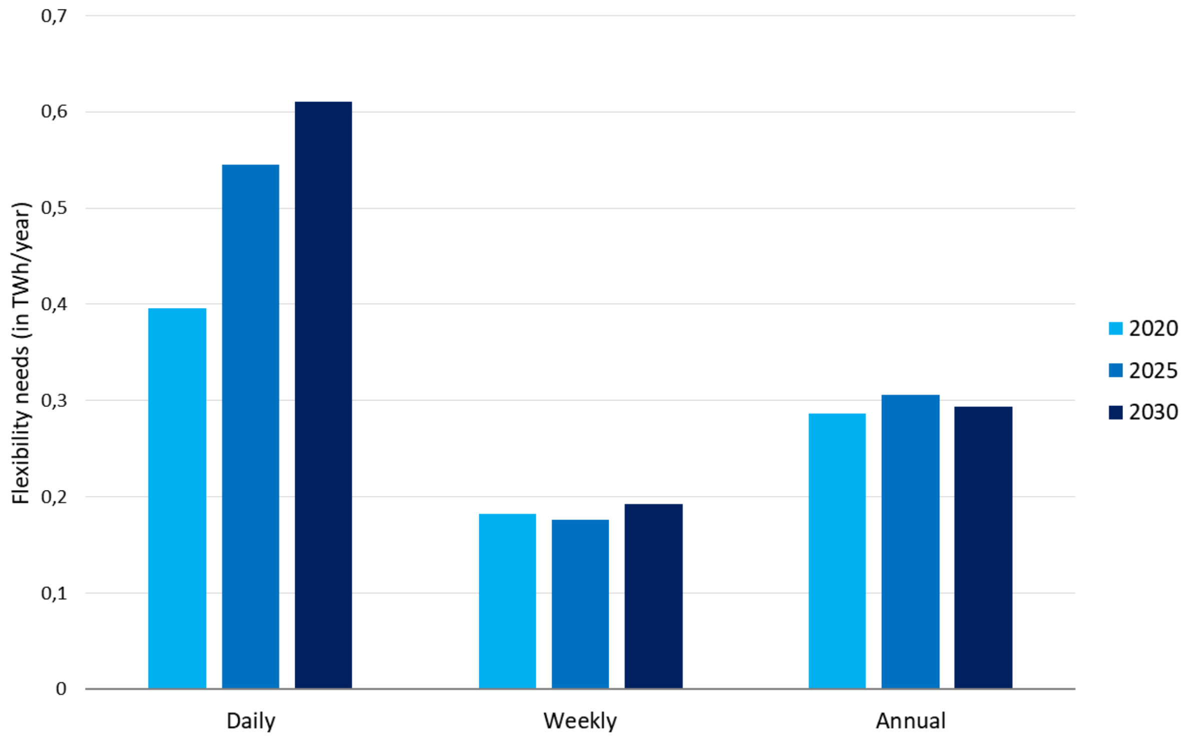

Figure 58 - Flexibility needs for 2020, 2025 and 2030

Flexibility portfolio

The following graph presents the potential for demand-response, storage and interconnectors, and the way these potentials are exploited in Options (II) and (III). Moreover, no batteries are found to be installed.

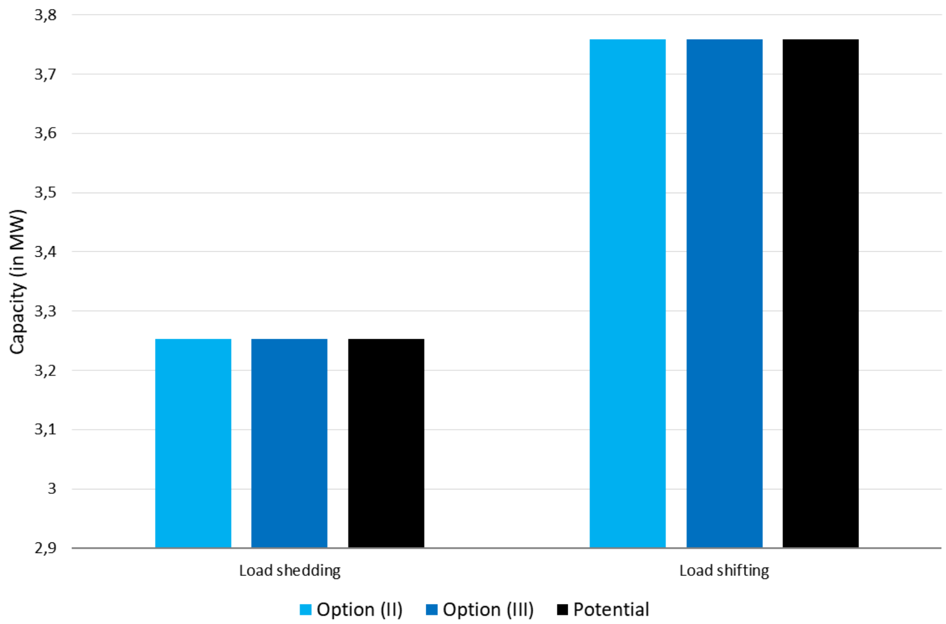

Figure 59 - Potential for flexibility solutions and installed capacities in Options (II) and (III)

Provision of flexibility

The following graph shows the contribution of each technology in the provision of daily, weekly and annual flexibility needs in Option (III).

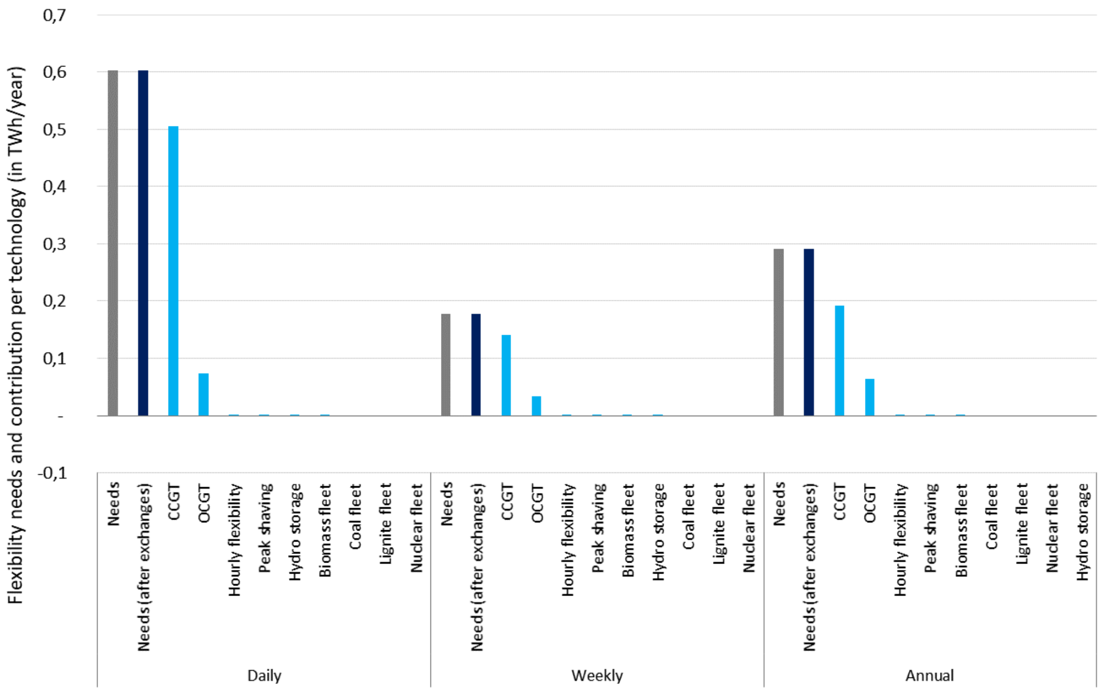

Figure 60: Contribution to flexibility needs per technology in Option (III)

Due to the lack of data, reserve procurement has not been modelled for this Member State.

Social welfare

The following table shows the evolution of the national social welfare between Option (II) and Option (I), and between Option (III) and Option (I), expressed in M€ per year.

The social welfare is defined as the sum of the producer surplus (driven by the difference between the market price and the variable generation cost), the consumer surplus (driven by the difference between what consumers would be ready to pay for electricity and the market price) and half the congestion rents (the revenues captured by interconnectors by exploiting the price difference between two zones).

The figures below do not take into account the savings in terms of investment costs, as these savings could be split between all the countries that have a common interest in a given project. At the EU28 level, compared to Option (I), these savings correspond to 150 M€ in Option (II) and to 210 M€ in Option (III).

	Evolution of social welfare (in M€ per year)
From Option (I) to Option (II)	+ 0.2 M€/y
From Option (I) to Option (III)	+ 0.1 M€/y

Table 27 - Evolution of social welfare

B.6 Czech Republic

Scenario description and flexibility needs

The following tables provide information related to the assumptions inherited from the PRIMES EUCO30 scenario.

	EUCO30
Power demand (in TWh/y)	71.6
Variable RES generation (in TWh/y)	8.8
of which wind onshore	*6.3*
of which wind offshore	*0.0*
of which PV	*2.5*

Table 28 - Demand and variable RES generation

Baseload and mid-merit capacities	EUCO30
Nuclear (in GW)	4.01
Coal (in GW)	1.60
Lignite (in GW)	7.20

Table 29 - Baseload and mid-merit capacities

The following graph presents the trajectory of flexibility needs over the 2020-2030 period.

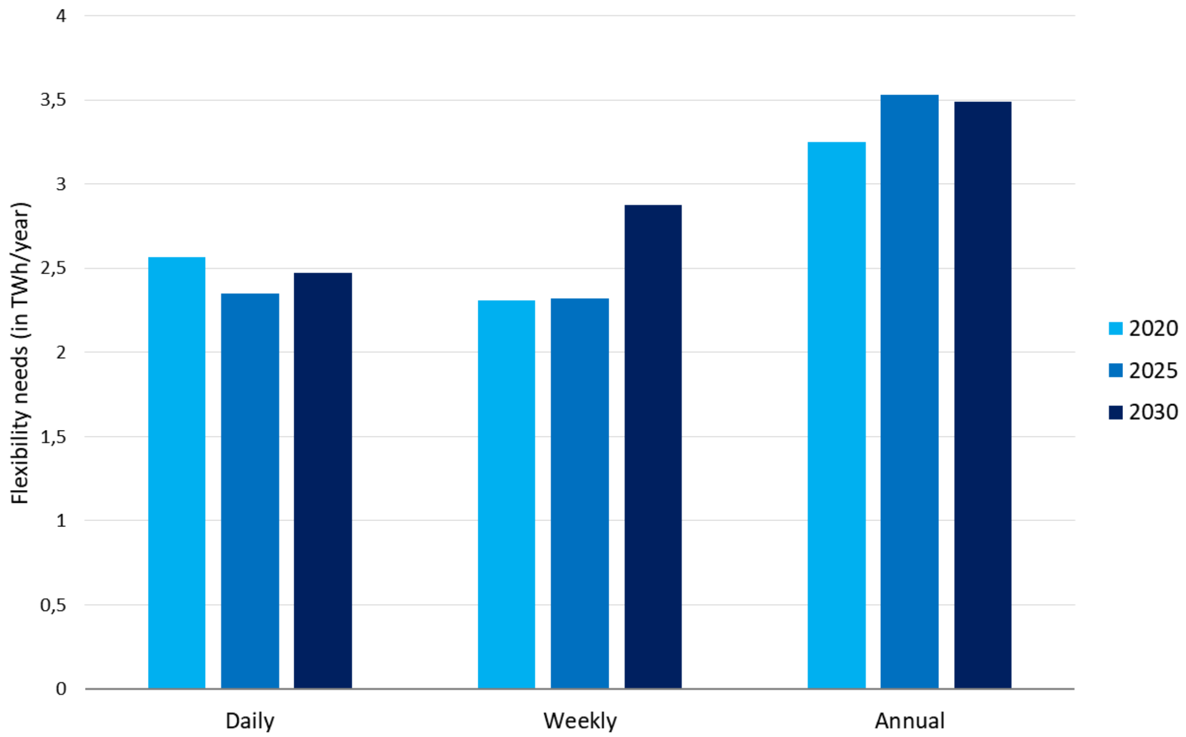

Figure 61 - Flexibility needs for 2020, 2025 and 2030

Flexibility portfolio

The following graph presents the potential for demand-response, storage and interconnectors, and the way these potentials are exploited in Options (II) and (III). Moreover, 5 MW of batteries are found to be installed in both Options (II) and (III).

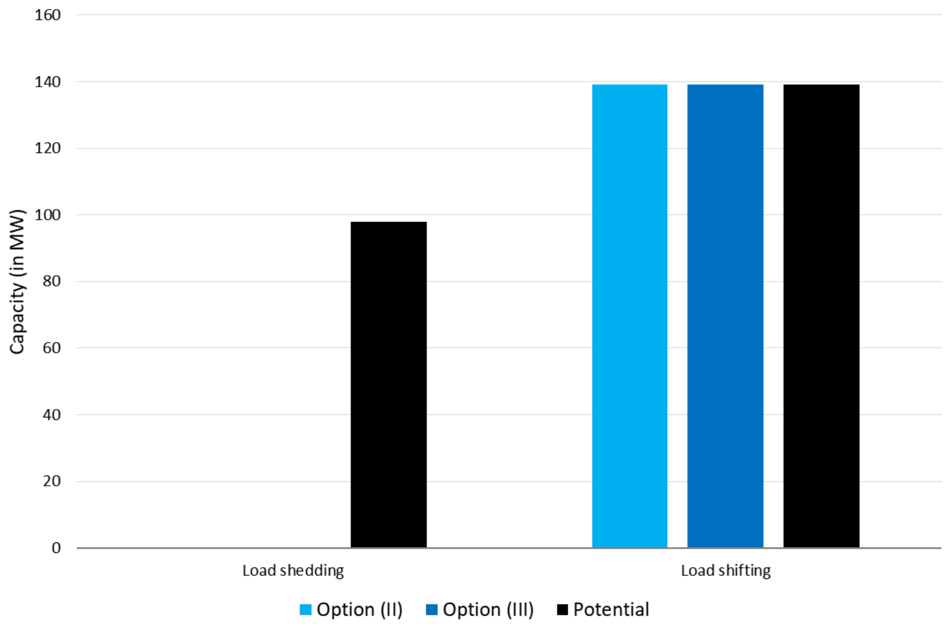

Figure 62 - Potential for flexibility solutions and installed capacities in Options (II) and (III)

Provision of flexibility

The following graph shows the contribution of each technology in the provision of daily, weekly and annual flexibility needs in Option (III).

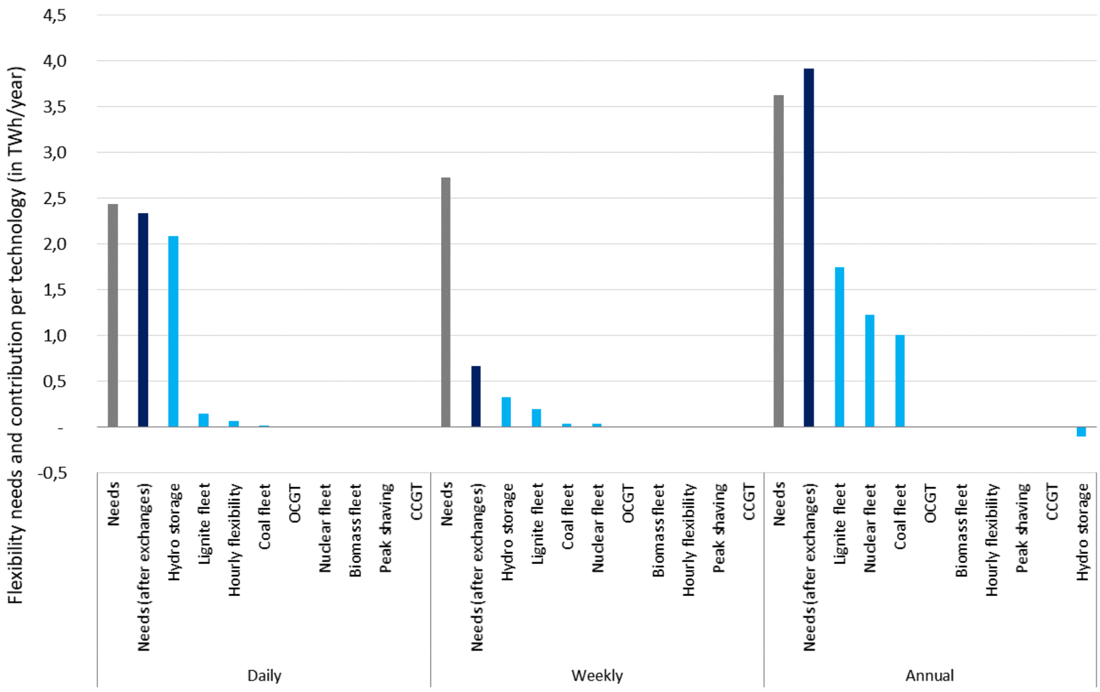

Figure 63: Contribution to flexibility needs per technology in Option (III)

The following graph shows the contribution of each technology to sub-hourly flexibility needs (i.e. participation in reserve procurement) in Option (III).

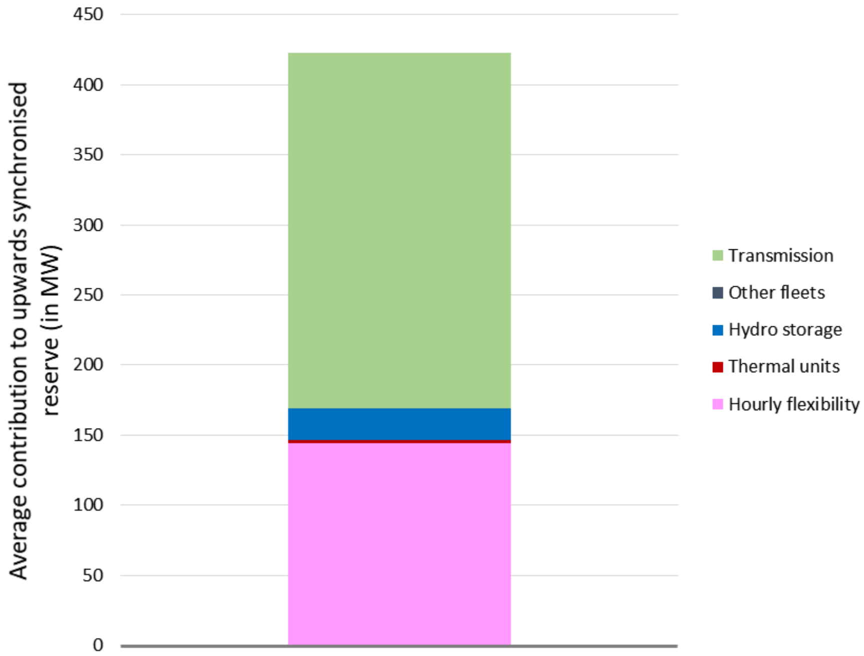

Figure 64: Contribution to upward synchronised reserve

Social welfare

The following table shows the evolution of the national social welfare between Option (II) and Option (I), and between Option (III) and Option (I), expressed in M€ per year.

The social welfare is defined as the sum of the producer surplus (driven by the difference between the market price and the variable generation cost), the consumer surplus (driven by the difference between what consumers would be ready to pay for electricity and the market price) and half the congestion rents (the revenues captured by interconnectors by exploiting the price difference between two zones).

The figures below do not take into account the savings in terms of investment costs, as these savings could be split between all the countries that have a common interest in a given project. At the EU28 level, compared to Option (I), these savings correspond to 150 M€ in Option (II) and to 210 M€ in Option (III).

	Evolution of social welfare (in M€ per year)
From Option (I) to Option (II)	+ 12 M€/y
From Option (I) to Option (III)	+ 34 M€/y

Table 30 - Evolution of social welfare

B.7 Denmark

Scenario description and flexibility needs

The following tables provide information related to the assumptions inherited from the PRIMES EUCO30 scenario.

	EUCO30
Power demand (in TWh/y)	39.2
Variable RES generation (in TWh/y)	24.4
of which wind onshore	*14.1*
of which wind offshore	*9.5*
of which PV	*0.8*

Table 31 - Demand and variable RES generation

Baseload and mid-merit capacities	EUCO30
Nuclear (in GW)	0.00
Coal (in GW)	1.47
Lignite (in GW)	0.00

Table 32 - Baseload and mid-merit capacities

The following graph presents the trajectory of flexibility needs over the 2020-2030 period.

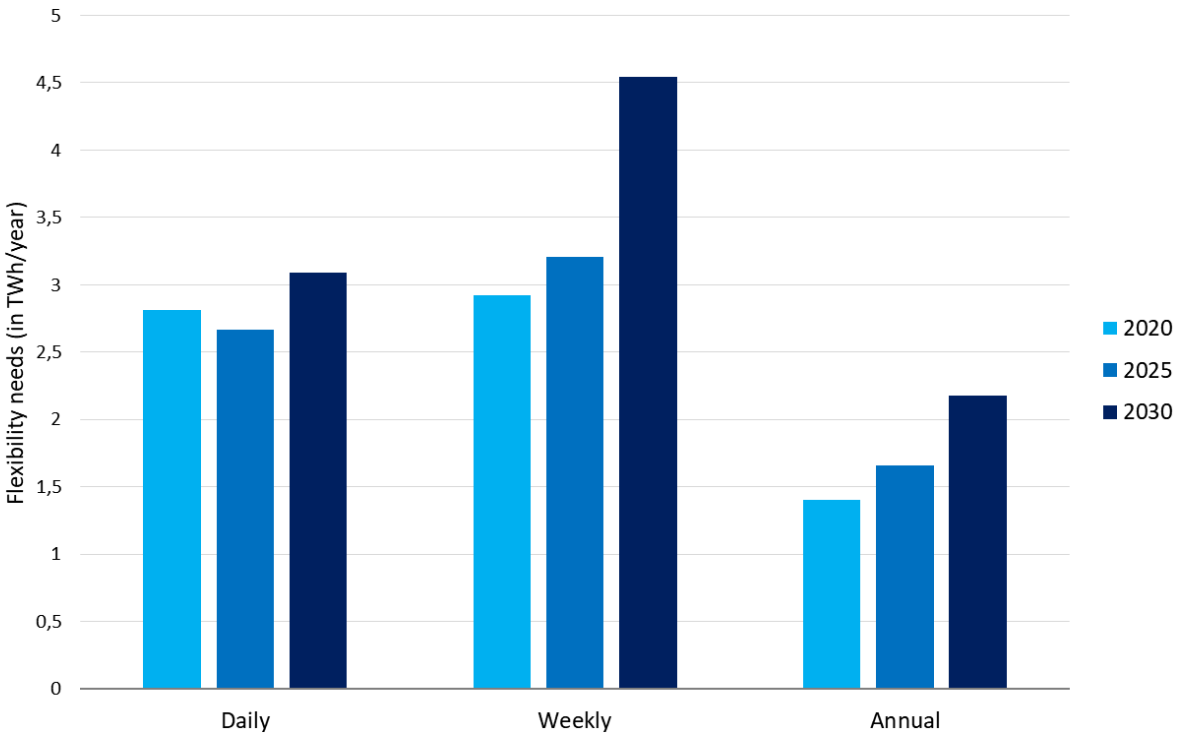

Figure 65 - Flexibility needs for 2020, 2025 and 2030

Flexibility portfolio

The following graph presents the potential for demand-response, storage and interconnectors, and the way these potentials are exploited in Options (II) and (III). Moreover, no batteries are found to be installed.

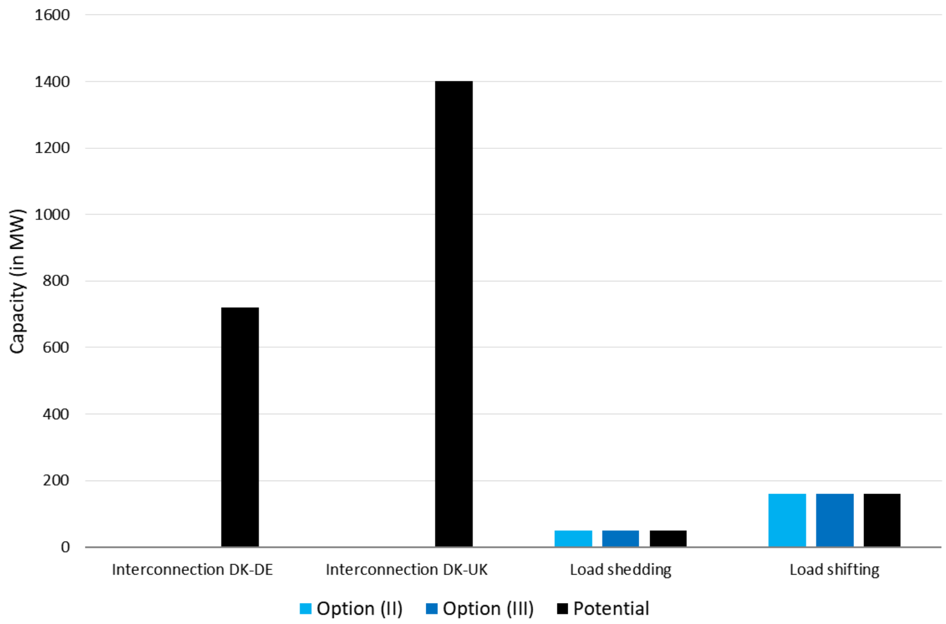

Figure 66 - Potential for flexibility solutions and installed capacities in Options (II) and (III)

Provision of flexibility

The following graph shows the contribution of each technology in the provision of daily, weekly and annual flexibility needs in Option (III).

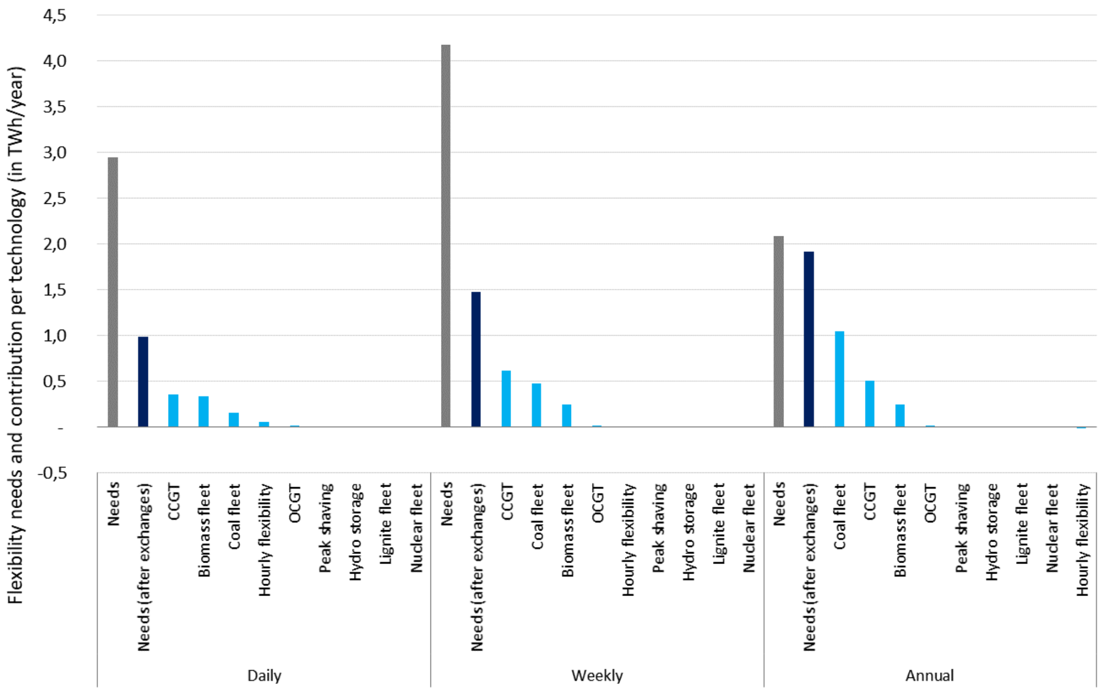

Figure 67: Contribution to flexibility needs per technology in Option (III)

The following graph shows the contribution of each technology to sub-hourly flexibility needs (i.e. participation in reserve procurement) in Option (III).

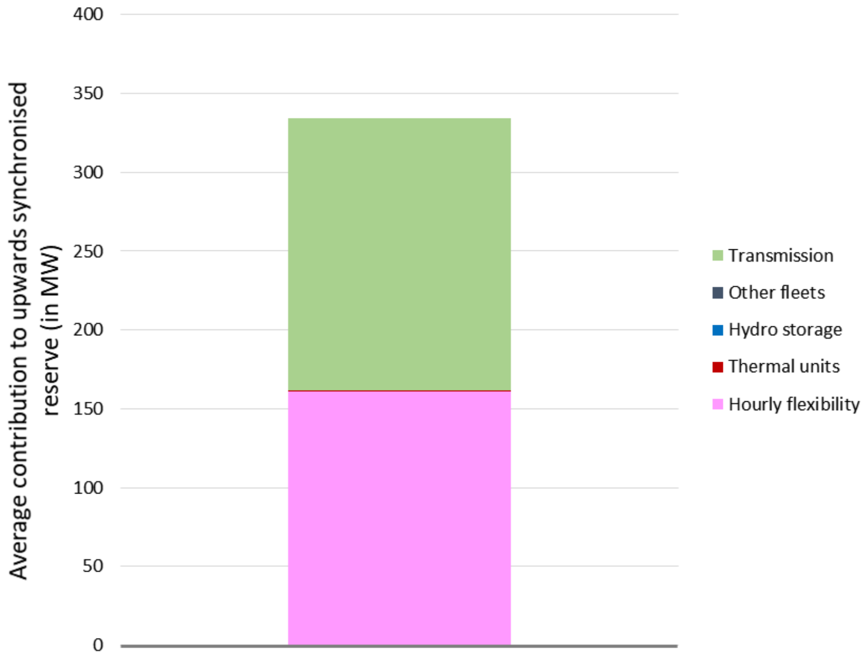

Figure 68: Contribution to upward synchronised reserve

Social welfare

The following table shows the evolution of the national social welfare between Option (II) and Option (I), and between Option (III) and Option (I), expressed in M€ per year.

The social welfare is defined as the sum of the producer surplus (driven by the difference between the market price and the variable generation cost), the consumer surplus (driven by the difference between what consumers would be ready to pay for electricity and the market price) and half the congestion rents (the revenues captured by interconnectors by exploiting the price difference between two zones).

The figures below do not take into account the savings in terms of investment costs, as these savings could be split between all the countries that have a common interest in a given project. At the EU28 level, compared to Option (I), these savings correspond to 150 M€ in Option (II) and to 210 M€ in Option (III).

	Evolution of social welfare (in M€ per year)
From Option (I) to Option (II)	+ 9 M€/y
From Option (I) to Option (III)	+ 10 M€/y

Table 33 - Evolution of social welfare

B.8 Estonia

Scenario description and flexibility needs

The following tables provide information related to the assumptions inherited from the PRIMES EUCO30 scenario.

	EUCO30
Power demand (in TWh/y)	9.3
Variable RES generation (in TWh/y)	1.2
of which wind onshore	*1.2*
of which wind offshore	*0.0*
of which PV	*0.0*

Table 34 - Demand and variable RES generation

Baseload and mid-merit capacities	EUCO30
Nuclear (in GW)	0.00
Coal (in GW)	0.00
Lignite (in GW)	1.41

Table 35 - Baseload and mid-merit capacities

The following graph presents the trajectory of flexibility needs over the 2020-2030 period.

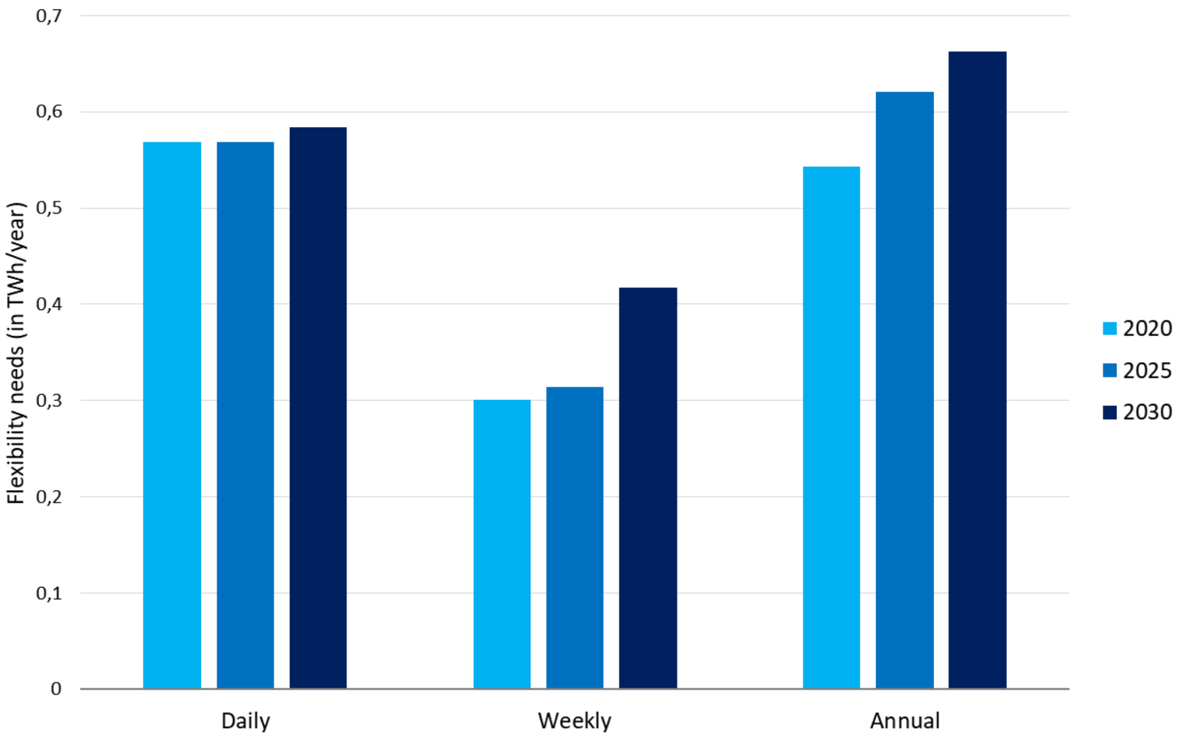

Figure 69 - Flexibility needs for 2020, 2025 and 2030

Flexibility portfolio

The following graph presents the potential for demand-response, storage and interconnectors, and the way these potentials are exploited in Options (II) and (III). Moreover, 35 MW of batteries are found to be installed in both Options (II) and (III).

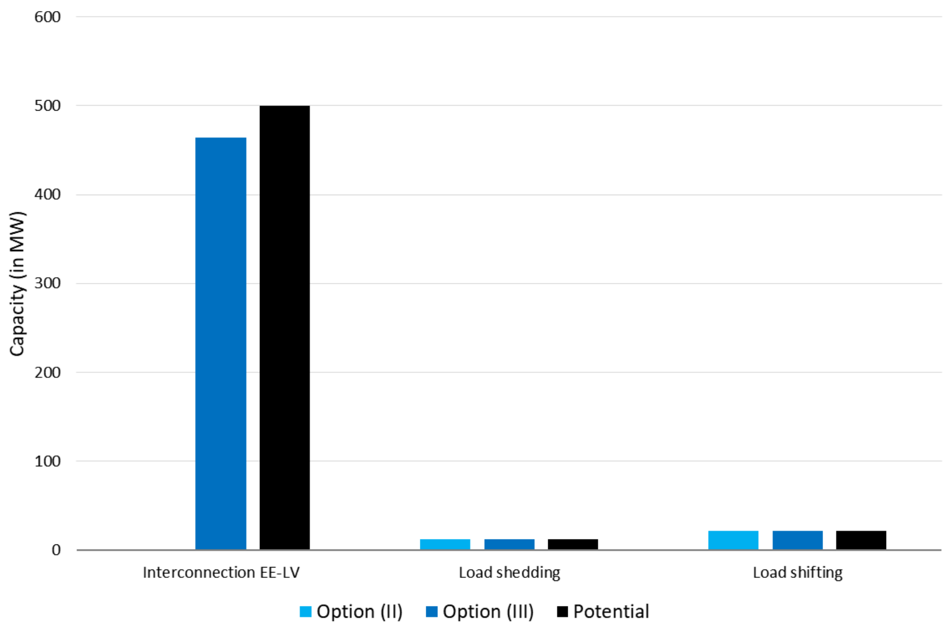

Figure 70 - Potential for flexibility solutions and installed capacities in Options (II) and (III)

Provision of flexibility

The following graph shows the contribution of each technology in the provision of daily, weekly and annual flexibility needs in Option (III).

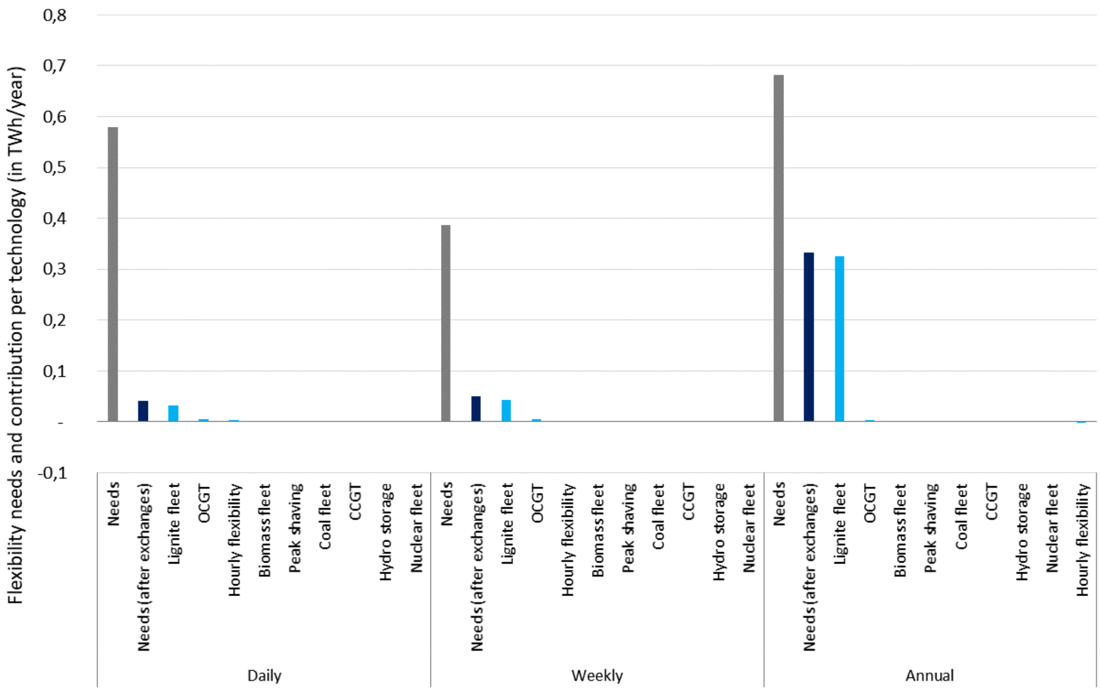

Figure 71: Contribution to flexibility needs per technology in Option (III)

The following graph shows the contribution of each technology to sub-hourly flexibility needs (i.e. participation in reserve procurement) in Option (III).

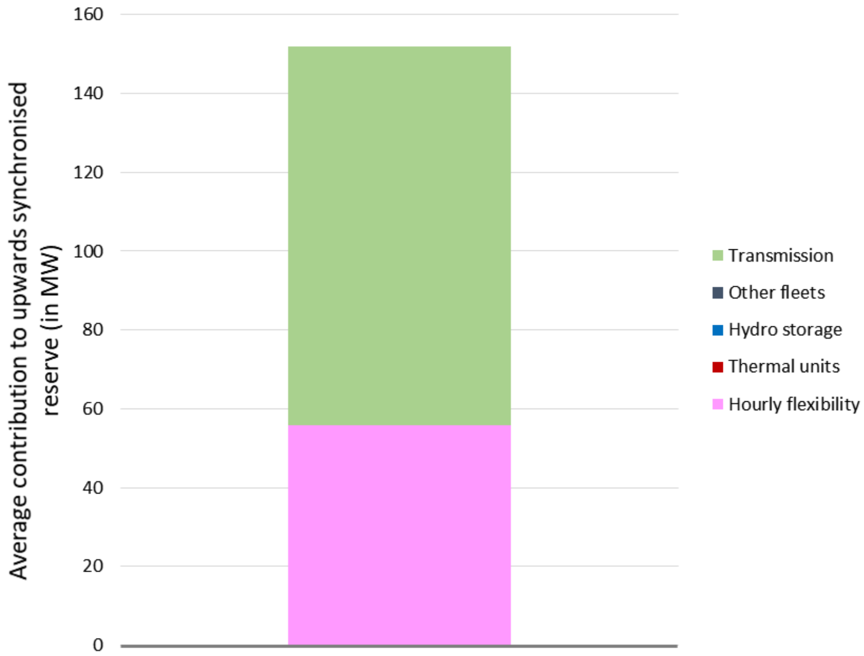

Figure 72: Contribution to upward synchronised reserve

Social welfare

The following table shows the evolution of the national social welfare between Option (II) and Option (I), and between Option (III) and Option (I), expressed in M€ per year.

The social welfare is defined as the sum of the producer surplus (driven by the difference between the market price and the variable generation cost), the consumer surplus (driven by the difference between what consumers would be ready to pay for electricity and the market price) and half the congestion rents (the revenues captured by interconnectors by exploiting the price difference between two zones).

The figures below do not take into account the savings in terms of investment costs, as these savings could be split between all the countries that have a common interest in a given project. At the EU28 level, compared to Option (I), these savings correspond to 150 M€ in Option (II) and to 210 M€ in Option (III).

	Evolution of social welfare (in M€ per year)
From Option (I) to Option (II)	+ 3 M€/y
From Option (I) to Option (III)	+ 12 M€/y

Table 36 - Evolution of social welfare

B.9 Finland

Scenario description and flexibility needs

The following tables provide information related to the assumptions inherited from the PRIMES EUCO30 scenario.

	EUCO30
Power demand (in TWh/y)	90.4
Variable RES generation (in TWh/y)	11.0
of which wind onshore	*10.6*
of which wind offshore	*0.3*
of which PV	*0.0*

Table 37 - Demand and variable RES generation

Baseload and mid-merit capacities	EUCO30
Nuclear (in GW)	3.40
Coal (in GW)	0.82
Lignite (in GW)	0.95

Table 38 - Baseload and mid-merit capacities

The following graph presents the trajectory of flexibility needs over the 2020-2030 period.

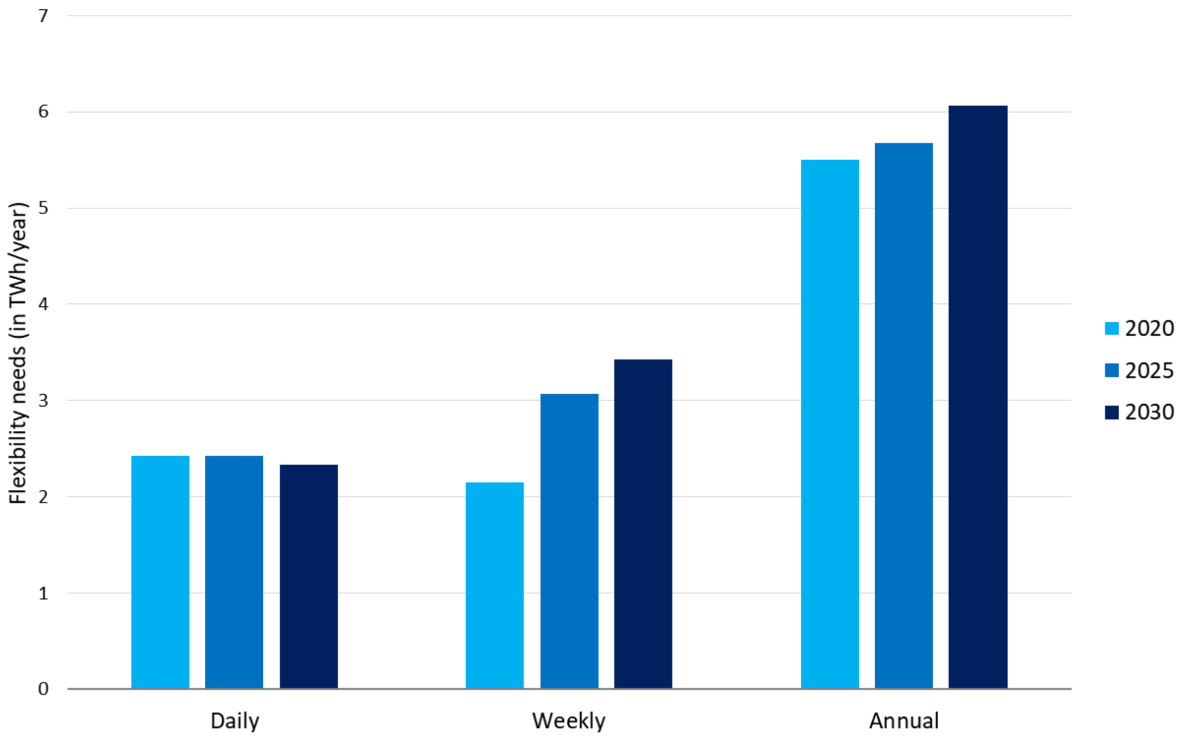

Figure 73 - Flexibility needs for 2020, 2025 and 2030

Flexibility portfolio

The following graph presents the potential for demand-response, storage and interconnectors, and the way these potentials are exploited in Options (II) and (III). Moreover, around 820 MW of batteries are found to be installed in Options (II) and (III)

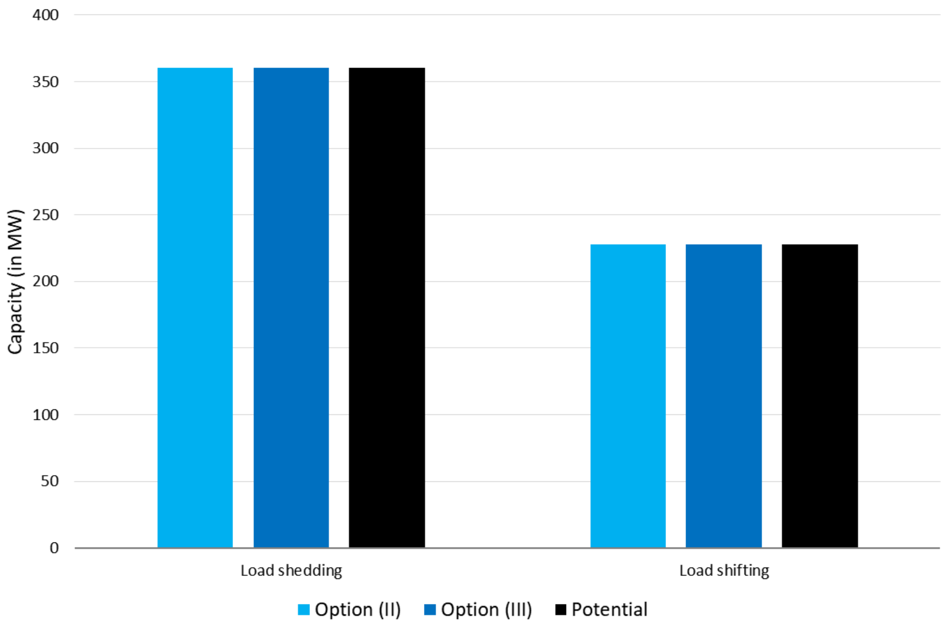

Figure 74: Potential for flexibility solutions and installed capacities in Options (II) and (III)

Provision of flexibility

The following graph shows the contribution of each technology in the provision of daily, weekly and annual flexibility needs in Option (III).

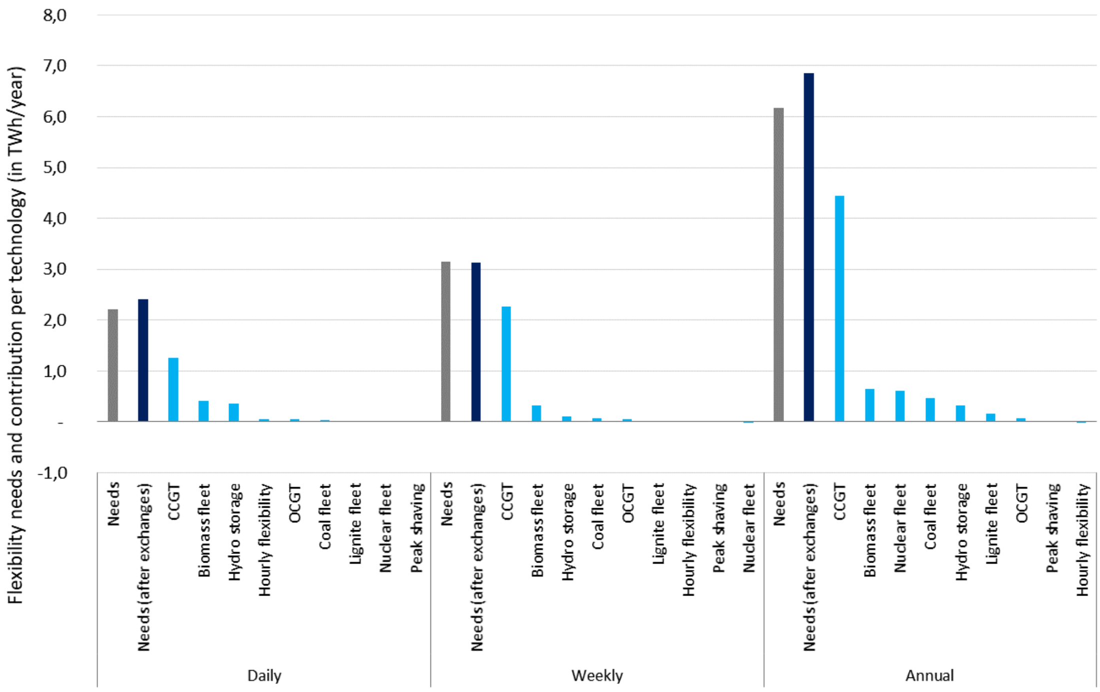

Figure 75: Contribution to flexibility needs per technology in Option (III)

The following graph shows the contribution of each technology to sub-hourly flexibility needs (i.e. participation in reserve procurement) in Option (III).

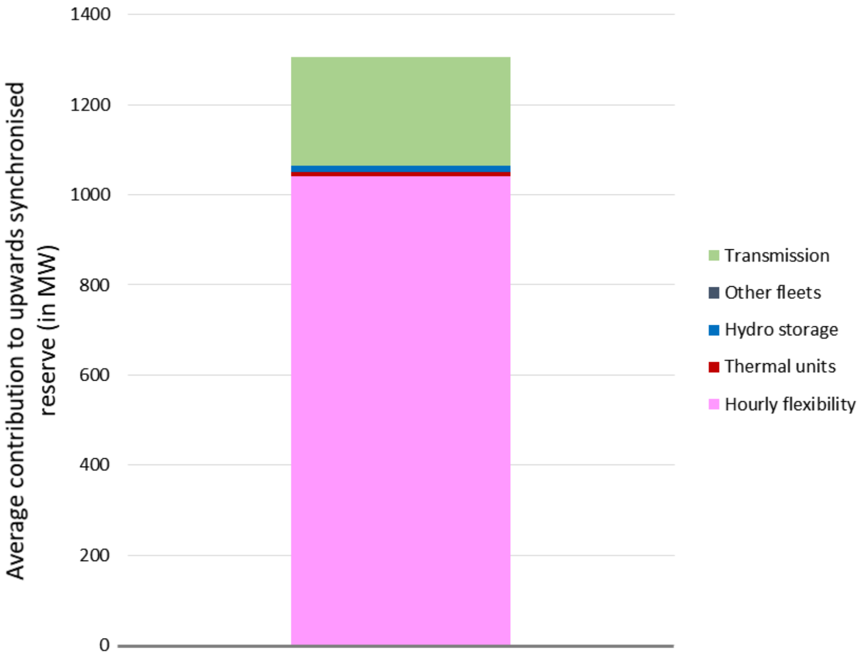

Figure 76: Contribution to upward synchronised reserve

Social welfare

The following table shows the evolution of the national social welfare between Option (II) and Option (I), and between Option (III) and Option (I), expressed in M€ per year.

The social welfare is defined as the sum of the producer surplus (driven by the difference between the market price and the variable generation cost), the consumer surplus (driven by the difference between what consumers would be ready to pay for electricity and the market price) and half the congestion rents (the revenues captured by interconnectors by exploiting the price difference between two zones).

The figures below do not take into account the savings in terms of investment costs, as these savings could be split between all the countries that have a common interest in a given project. At the EU28 level, compared to Option (I), these savings correspond to 150 M€ in Option (II) and to 210 M€ in Option (III).

	Evolution of social welfare (in M€ per year)
From Option (I) to Option (II)	+ 120 M€/y
From Option (I) to Option (III)	+ 130 M€/y

Table 39 - Evolution of social welfare

B.10 France

Scenario description and flexibility needs

The following tables provide information related to the assumptions inherited from the PRIMES EUCO30 scenario.

	EUCO30
Power demand (in TWh/y)	499.8
Variable RES generation (in TWh/y)	110.7
of which wind onshore	*45.1*
of which wind offshore	*20.3*
of which PV	*45.3*

Table 40 - Demand and variable RES generation

Baseload and mid-merit capacities	EUCO30
Nuclear (in GW)	59.49
Coal (in GW)	3.78
Lignite (in GW)	0.00

Table 41 - Baseload and mid-merit capacities

The following graph presents the trajectory of flexibility needs over the 2020-2030 period.

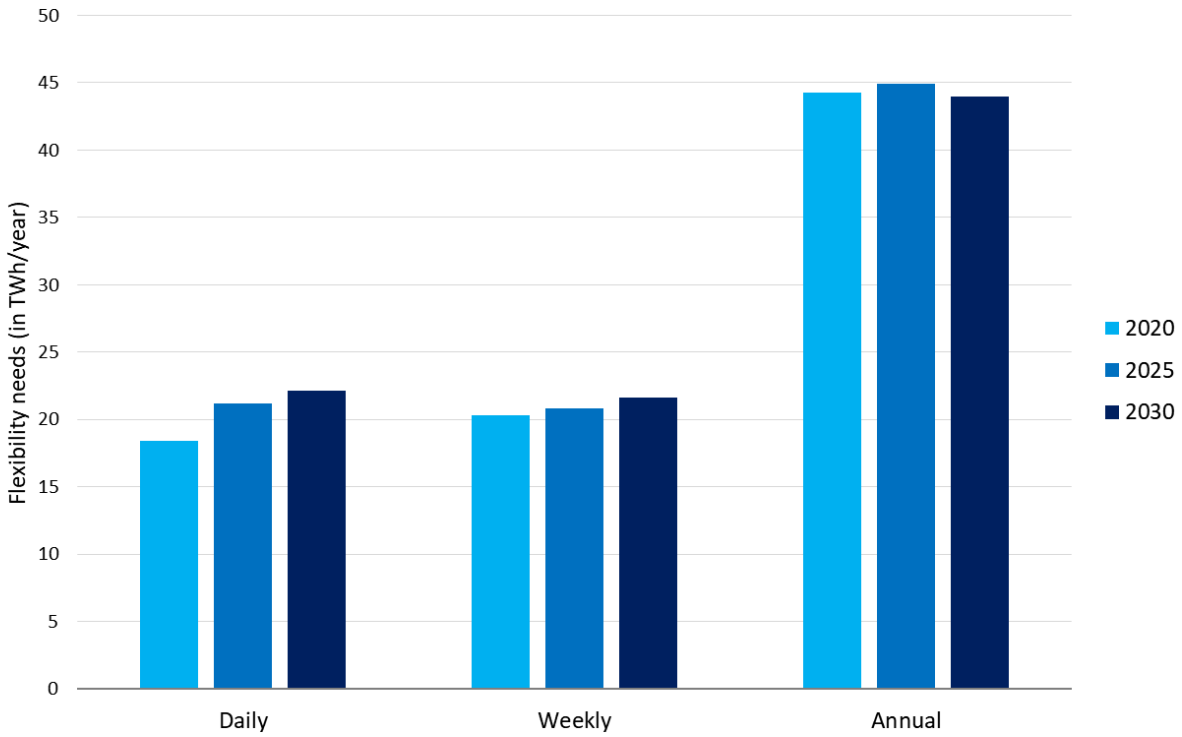

Figure 77 - Flexibility needs for 2020, 2025 and 2030

Flexibility portfolio

The following graph presents the potential for demand-response, storage and interconnectors, and the way these potentials are exploited in Options (II) and (III). Moreover, no batteries are found to be installed.

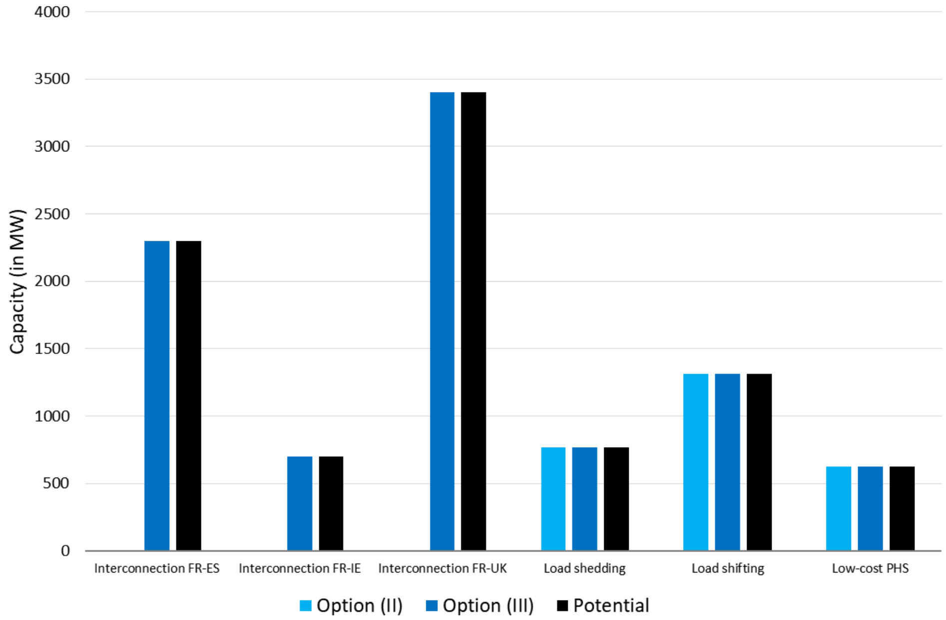

Figure 78 - Potential for flexibility solutions and installed capacities in Options (II) and (III)

Provision of flexibility

The following graph shows the contribution of each technology in the provision of daily, weekly and annual flexibility needs in Option (III).

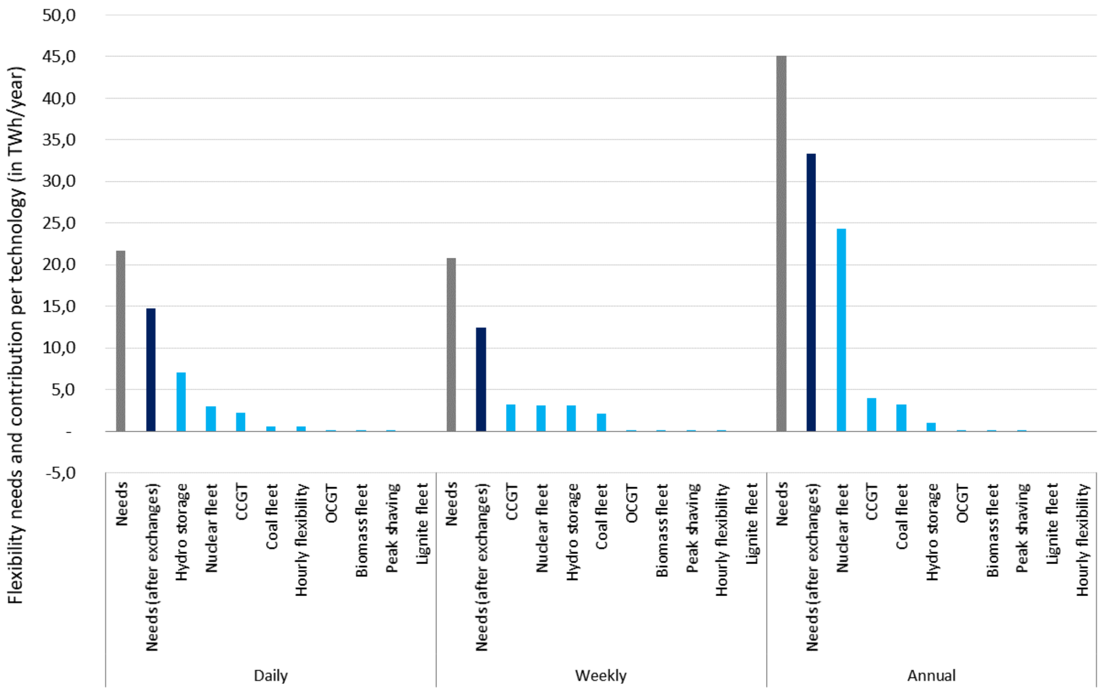

Figure 79: Contribution to flexibility needs per technology in Option (III)

The following graph shows the contribution of each technology to sub-hourly flexibility needs (i.e. participation in reserve procurement) in Option (III).

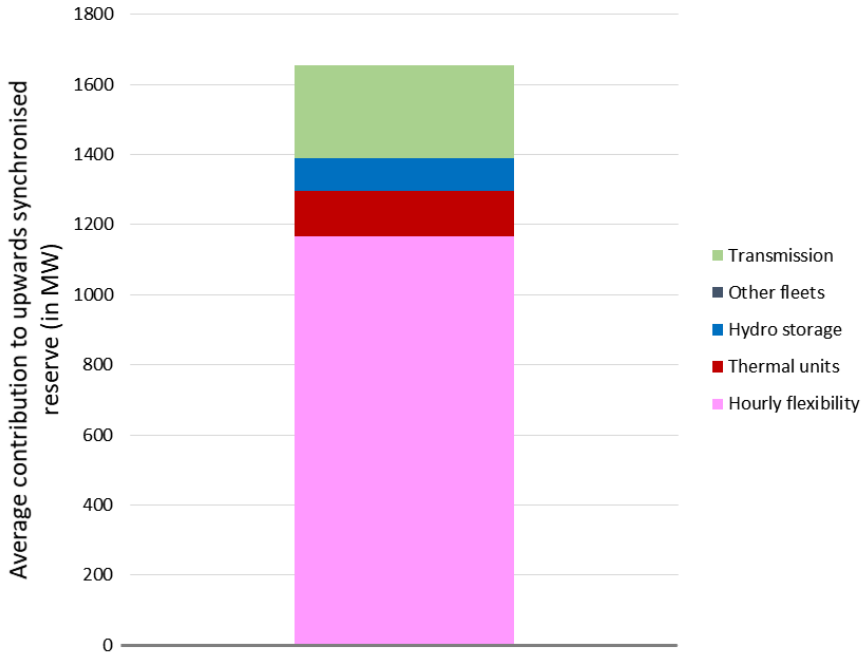

Figure 80: Contribution to upward synchronised reserve

Social welfare

The following table shows the evolution of the national social welfare between Option (II) and Option (I), and between Option (III) and Option (I), expressed in M€ per year.

The social welfare is defined as the sum of the producer surplus (driven by the difference between the market price and the variable generation cost), the consumer surplus (driven by the difference between what consumers would be ready to pay for electricity and the market price) and half the congestion rents (the revenues captured by interconnectors by exploiting the price difference between two zones).

The figures below do not take into account the savings in terms of investment costs, as these savings could be split between all the countries that have a common interest in a given project. At the EU28 level, compared to Option (I), these savings correspond to 150 M€ in Option (II) and to 210 M€ in Option (III).

	Evolution of social welfare (in M€ per year)
From Option (I) to Option (II)	+ 260 M€/y
From Option (I) to Option (III)	+ 1 000 M€/y

Table 42 - Evolution of social welfare

B.11 Germany

Scenario description and flexibility needs

The following tables provide information related to the assumptions inherited from the PRIMES EUCO30 scenario.

	EUCO30
Power demand (in TWh/y)	577.4
Variable RES generation (in TWh/y)	211.3
of which wind onshore	*100.4*
of which wind offshore	*31.5*
of which PV	*79.3*

Table 43 - Demand and variable RES generation

Baseload and mid-merit capacities	EUCO30
Nuclear (in GW)	0.00
Coal (in GW)	22.93
Lignite (in GW)	13.78

Table 44 - Baseload and mid-merit capacities

The following graph presents the trajectory of flexibility needs over the 2020-2030 period.

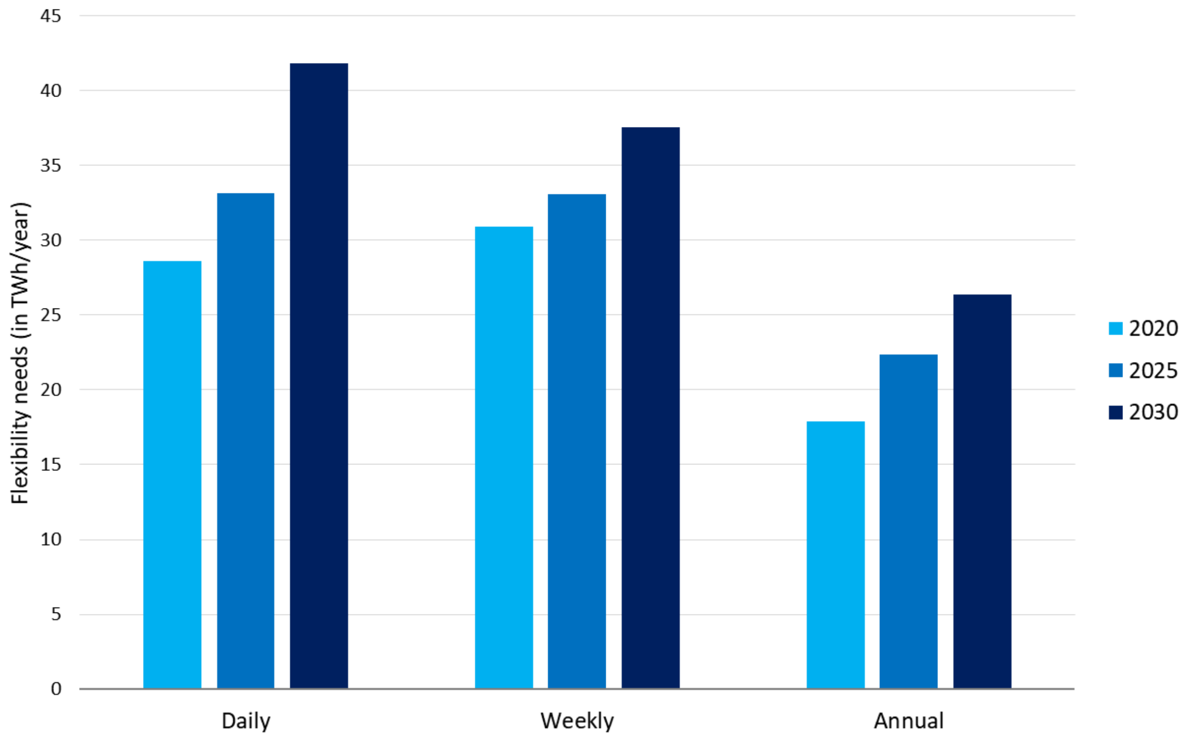

Figure 81 - Flexibility needs for 2020, 2025 and 2030

Flexibility portfolio

The following graph presents the potential for demand-response, storage and interconnectors, and the way these potentials are exploited in Options (II) and (III). Moreover, no batteries are found to be installed.

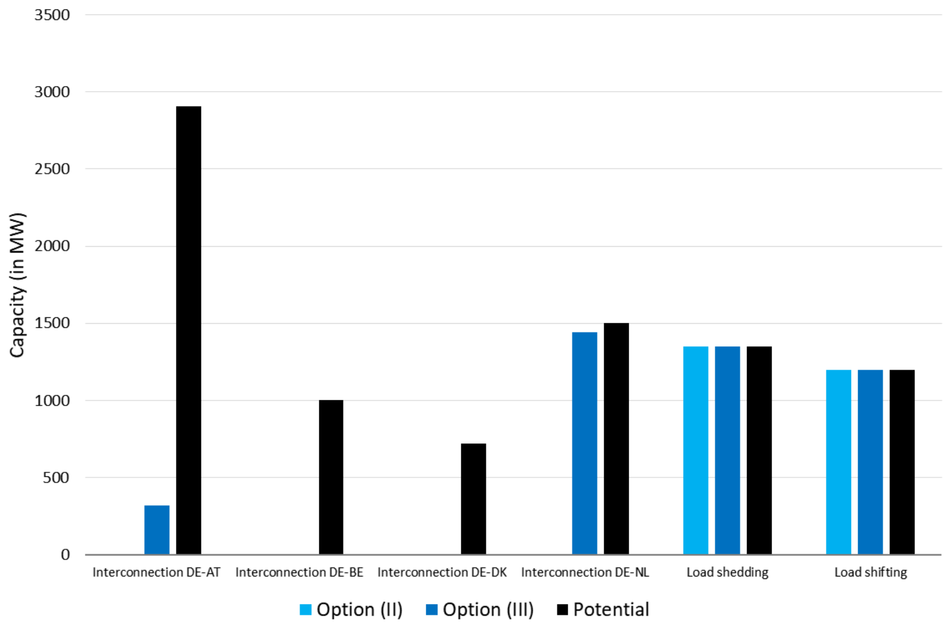

Figure 82 - Potential for flexibility solutions and installed capacities in Options (II) and (III)

Provision of flexibility

The following graph shows the contribution of each technology in the provision of daily, weekly and annual flexibility needs in Option (III).

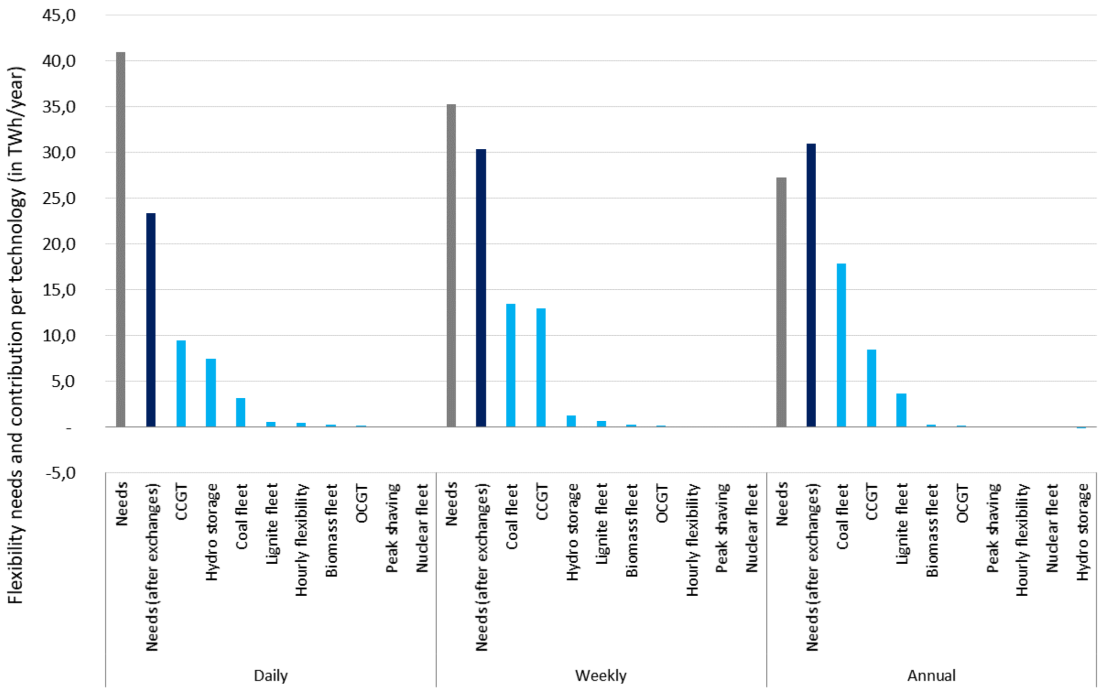

Figure 83: Contribution to flexibility needs per technology in Option (III)

The following graph shows the contribution of each technology to sub-hourly flexibility needs (i.e. participation in reserve procurement) in Option (III).

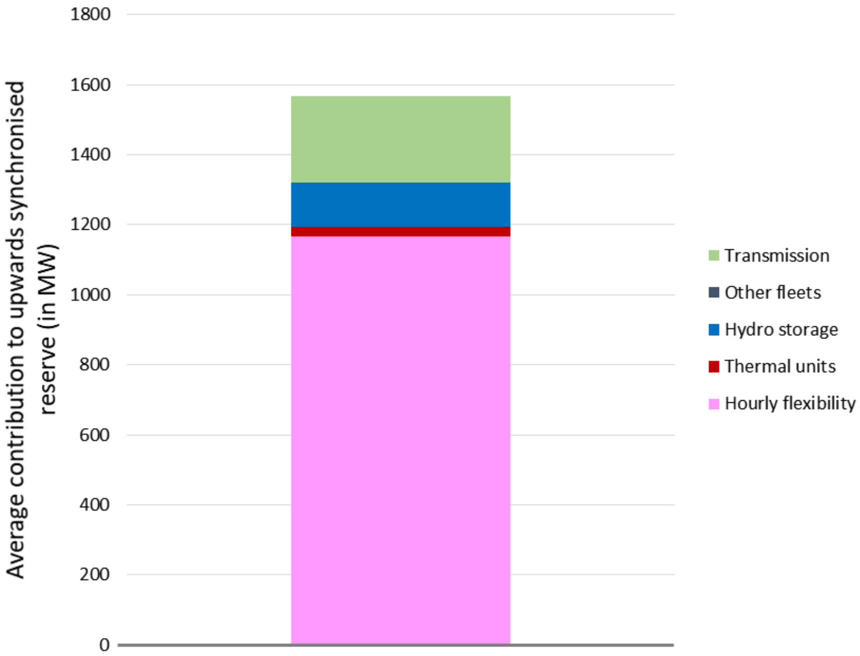

Figure 84: Contribution to upward synchronised reserve

Social welfare

The following table shows the evolution of the national social welfare between Option (II) and Option (I), and between Option (III) and Option (I), expressed in M€ per year.

The social welfare is defined as the sum of the producer surplus (driven by the difference between the market price and the variable generation cost), the consumer surplus (driven by the difference between what consumers would be ready to pay for electricity and the market price) and half the congestion rents (the revenues captured by interconnectors by exploiting the price difference between two zones).

The figures below do not take into account the savings in terms of investment costs, as these savings could be split between all the countries that have a common interest in a given project. At the EU28 level, compared to Option (I), these savings correspond to 150 M€ in Option (II) and to 210 M€ in Option (III).

	Evolution of social welfare (in M€ per year)
From Option (I) to Option (II)	+ 120 M€/y
From Option (I) to Option (III)	+ 32 M€/y

Table 45 - Evolution of social welfare

B.12 Greece

Scenario description and flexibility needs

The following tables provide information related to the assumptions inherited from the PRIMES EUCO30 scenario.

	EUCO30
Power demand (in TWh/y)	51.3
Variable RES generation (in TWh/y)	30.8
of which wind onshore	*18.7*
of which wind offshore	*0.0*
of which PV	*12.0*

Table 46 - Demand and variable RES generation

Baseload and mid-merit capacities	EUCO30
Nuclear (in GW)	0.00
Coal (in GW)	0.00
Lignite (in GW)	2.87

Table 47 - Baseload and mid-merit capacities

The following graph presents the trajectory of flexibility needs over the 2020-2030 period.

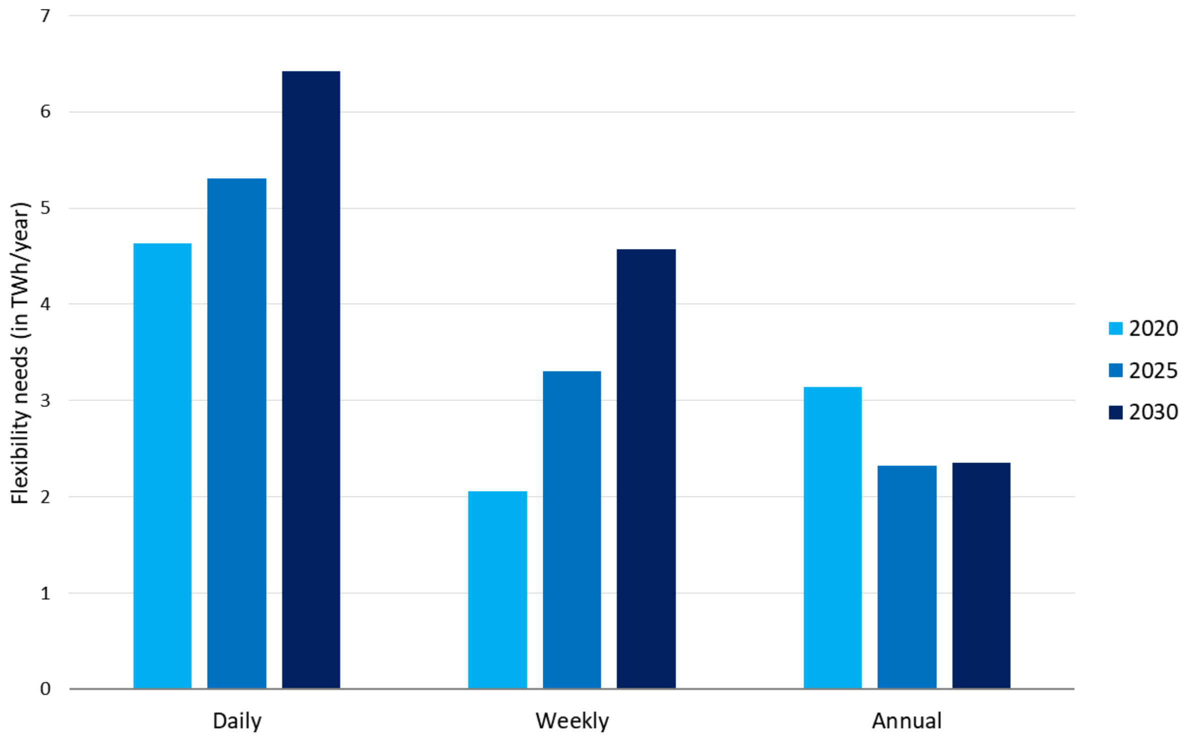

Figure 85 - Flexibility needs for 2020, 2025 and 2030

Flexibility portfolio

The following graph presents the potential for demand-response, storage and interconnectors, and the way these potentials are exploited in Options (II) and (III). Moreover, no batteries are found to be installed.

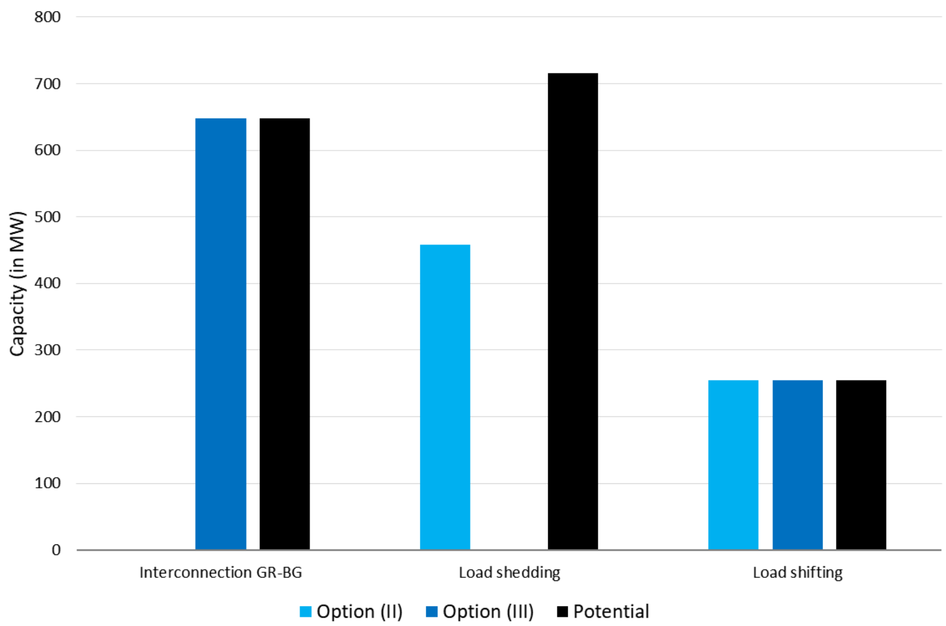

Figure 86 - Potential for flexibility solutions and installed capacities in Options (II) and (III)

Provision of flexibility

The following graph shows the contribution of each technology in the provision of daily, weekly and annual flexibility needs in Option (III).

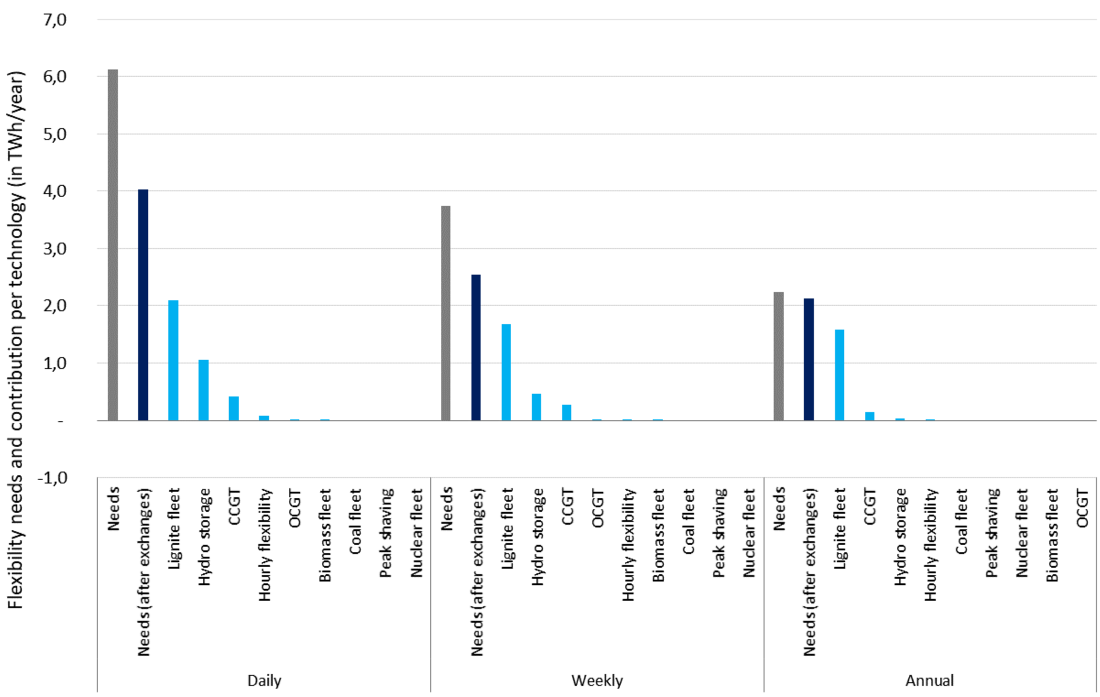

Figure 87: Contribution to flexibility needs per technology in Option (III)

The following graph shows the contribution of each technology to sub-hourly flexibility needs (i.e. participation in reserve procurement) in Option (III).

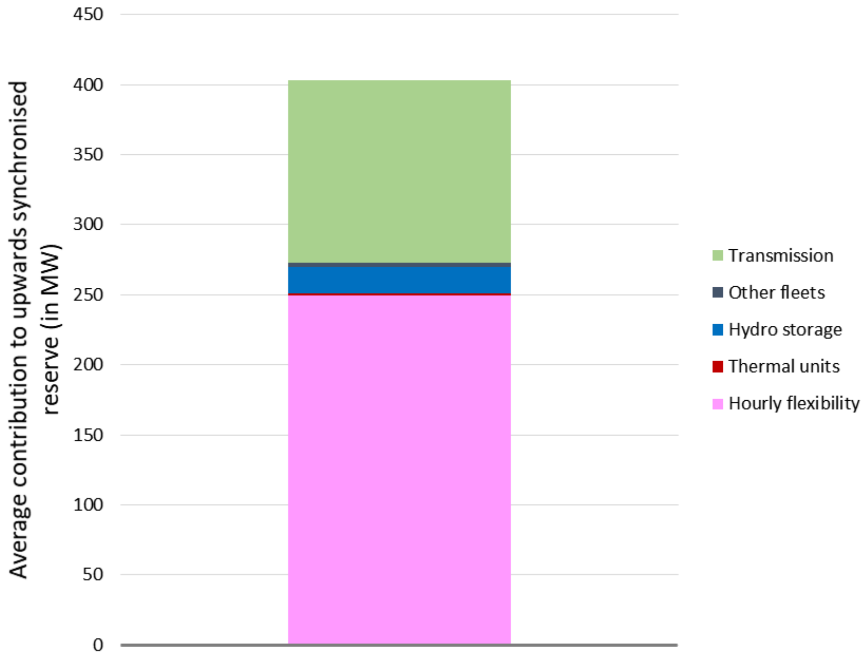

Figure 88: Contribution to upward synchronised reserve

Social welfare

The following table shows the evolution of the national social welfare between Option (II) and Option (I), and between Option (III) and Option (I), expressed in M€ per year.

The social welfare is defined as the sum of the producer surplus (driven by the difference between the market price and the variable generation cost), the consumer surplus (driven by the difference between what consumers would be ready to pay for electricity and the market price) and half the congestion rents (the revenues captured by interconnectors by exploiting the price difference between two zones).

The figures below do not take into account the savings in terms of investment costs, as these savings could be split between all the countries that have a common interest in a given project. At the EU28 level, compared to Option (I), these savings correspond to 150 M€ in Option (II) and to 210 M€ in Option (III).

	Evolution of social welfare (in M€ per year)
From Option (I) to Option (II)	+ 82 M€/y
From Option (I) to Option (III)	+ 110 M€/y

Table 48 - Evolution of social welfare

B.13 Hungary

Scenario description and flexibility needs

The following tables provide information related to the assumptions inherited from the PRIMES EUCO30 scenario.

	EUCO30
Power demand (in TWh/y)	42.5
Variable RES generation (in TWh/y)	4.3
of which wind onshore	*2.5*
of which wind offshore	*0.0*
of which PV	*1.9*

Table 49 - Demand and variable RES generation

Baseload and mid-merit capacities	EUCO30
Nuclear (in GW)	4.48
Coal (in GW)	0.00
Lignite (in GW)	0.41

Table 50 - Baseload and mid-merit capacities

The following graph presents the trajectory of flexibility needs over the 2020-2030 period.

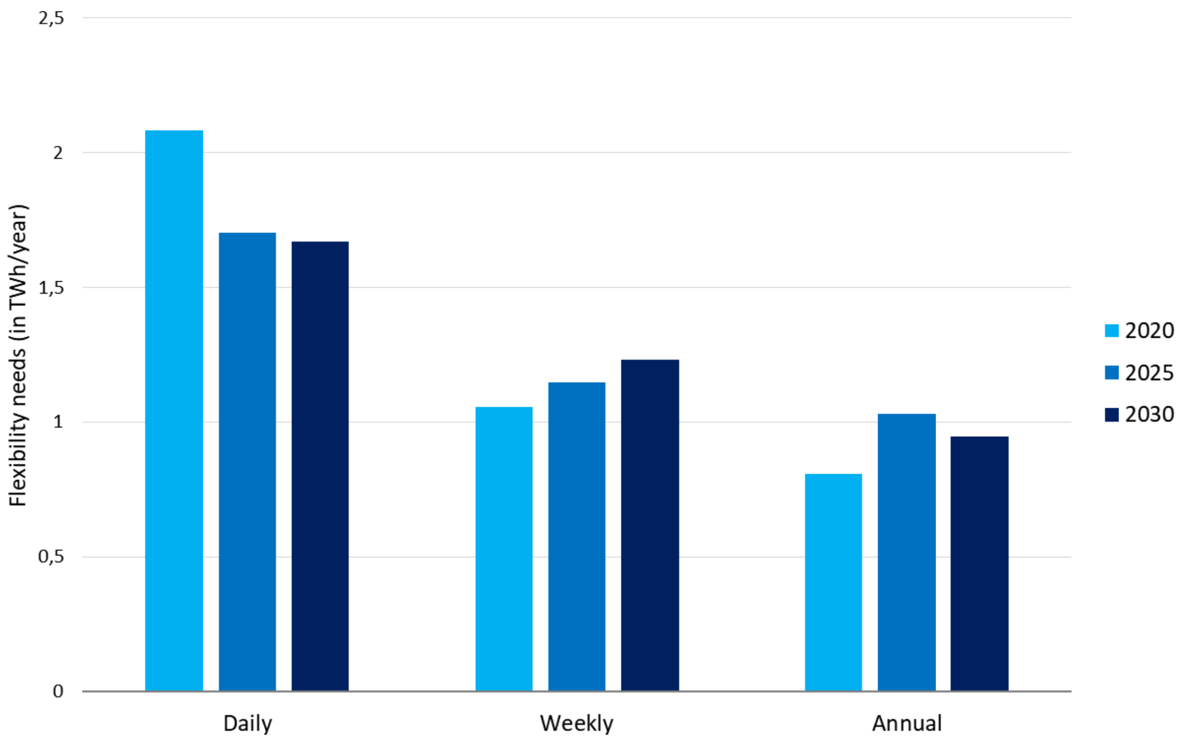

Figure 89 - Flexibility needs for 2020, 2025 and 2030

Flexibility portfolio

The following graph presents the potential for demand-response, storage and interconnectors, and the way these potentials are exploited in Options (II) and (III). Moreover, 30 MW of batteries are found to be installed in Options (II) and (III).

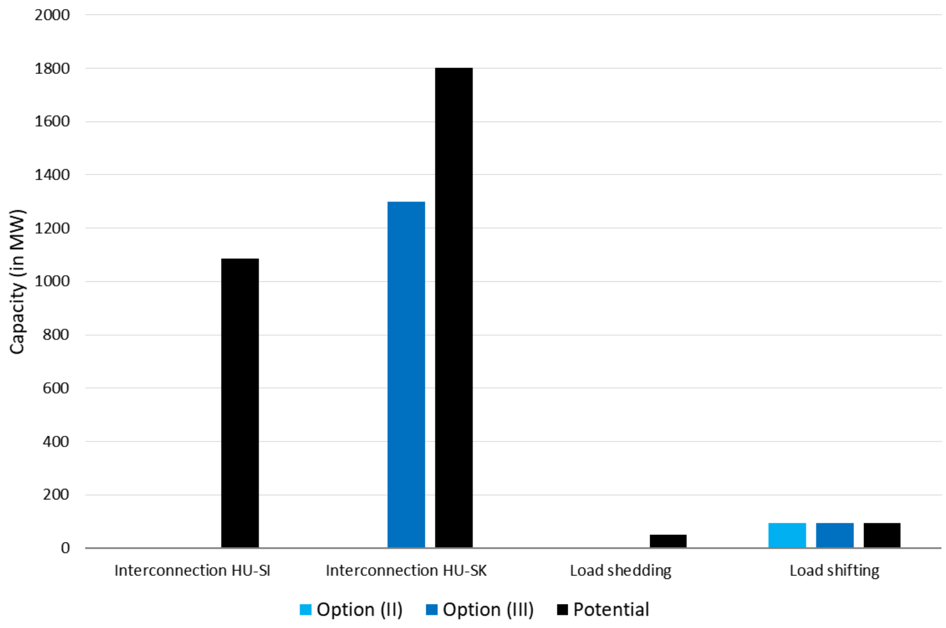

Figure 90 - Potential for flexibility solutions and installed capacities in Options (II) and (III)

Provision of flexibility

The following graph shows the contribution of each technology in the provision of daily, weekly and annual flexibility needs in Option (III).

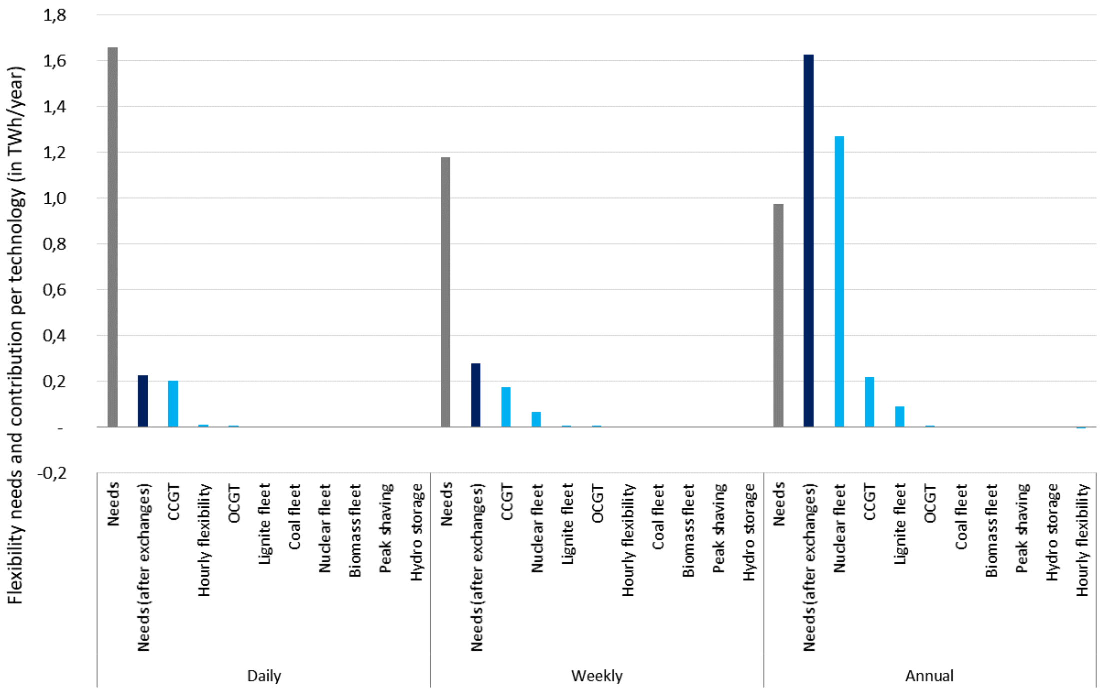

Figure 91: Contribution to flexibility needs per technology in Option (III)

The following graph shows the contribution of each technology to sub-hourly flexibility needs (i.e. participation in reserve procurement) in Option (III).

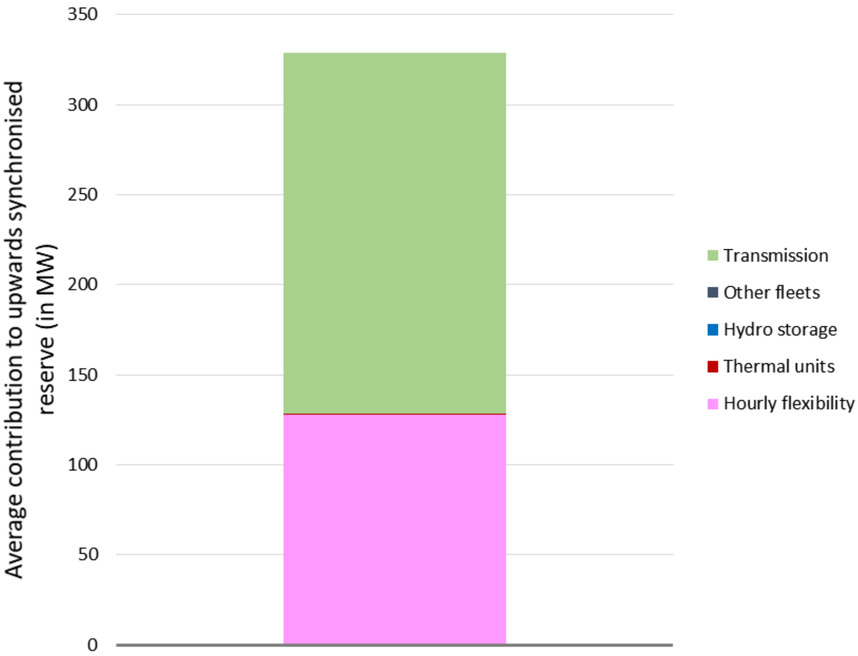

Figure 92: Contribution to upward synchronised reserve

Social welfare

The following table shows the evolution of the national social welfare between Option (II) and Option (I), and between Option (III) and Option (I), expressed in M€ per year.

The social welfare is defined as the sum of the producer surplus (driven by the difference between the market price and the variable generation cost), the consumer surplus (driven by the difference between what consumers would be ready to pay for electricity and the market price) and half the congestion rents (the revenues captured by interconnectors by exploiting the price difference between two zones).

The figures below do not take into account the savings in terms of investment costs, as these savings could be split between all the countries that have a common interest in a given project. At the EU28 level, compared to Option (I), these savings correspond to 150 M€ in Option (II) and to 210 M€ in Option (III).

	Evolution of social welfare (in M€ per year)
From Option (I) to Option (II)	+ 14 M€/y
From Option (I) to Option (III)	+ 14 M€/y

Table 51 - Evolution of social welfare

B.14 Ireland

Scenario description and flexibility needs

The following tables provide information related to the assumptions inherited from the PRIMES EUCO30 scenario.

	EUCO30
Power demand (in TWh/y)	30.0
Variable RES generation (in TWh/y)	14.9
of which wind onshore	*14.4*
of which wind offshore	*0.4*
of which PV	*0.0*

Table 52 - Demand and variable RES generation

Baseload and mid-merit capacities	EUCO30
Nuclear (in GW)	0.00
Coal (in GW)	0.84
Lignite (in GW)	0.00

Table 53 - Baseload and mid-merit capacities

The following graph presents the trajectory of flexibility needs over the 2020-2030 period.

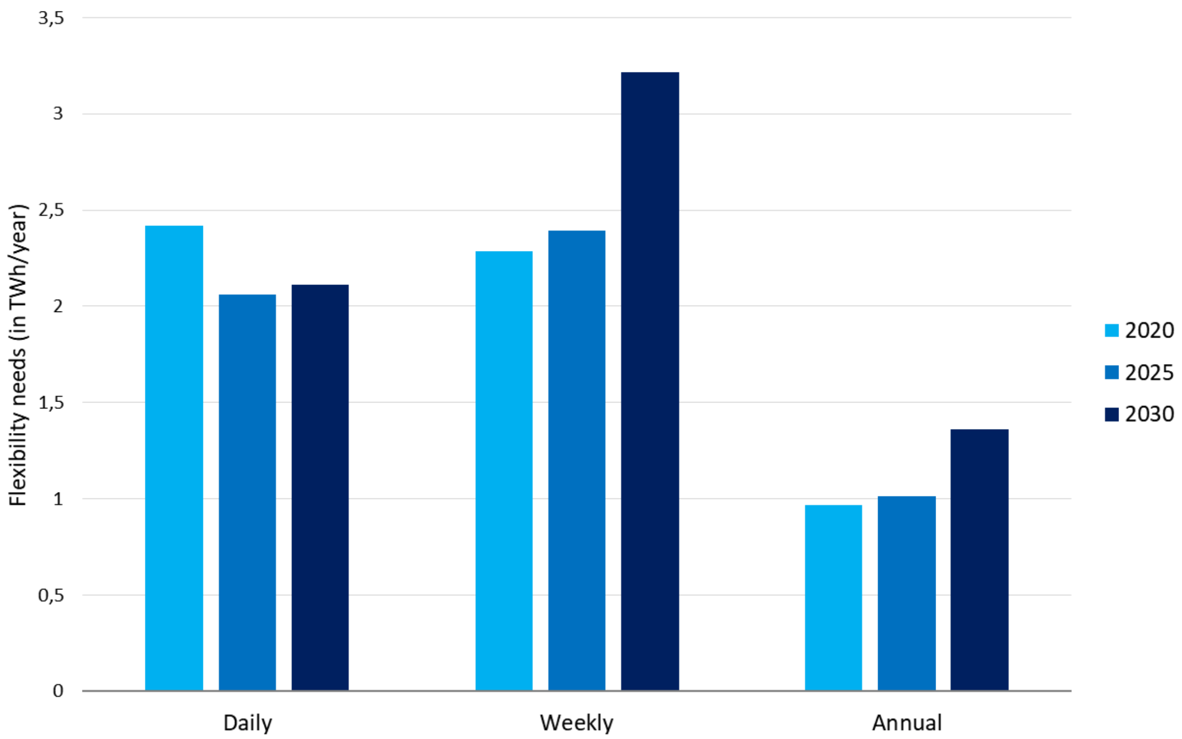

Figure 93 - Flexibility needs for 2020, 2025 and 2030

Flexibility portfolio

The following graph presents the potential for demand-response, storage and interconnectors, and the way these potentials are exploited in Options (II) and (III). Moreover, 60 MW of batteries are found to be installed in Options (II) and (III).

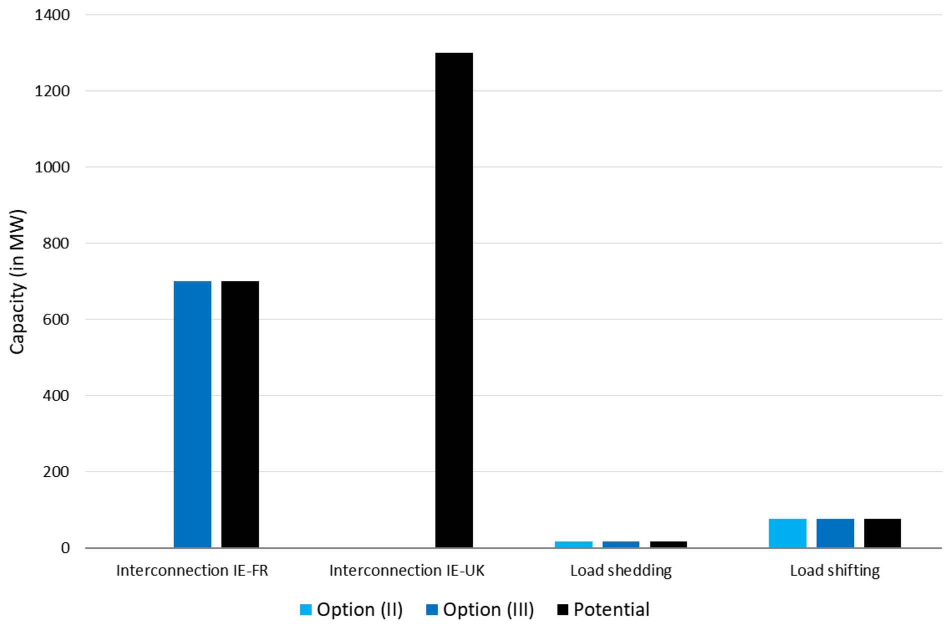

Figure 94 - Potential for flexibility solutions and installed capacities in Options (II) and (III)

Provision of flexibility

The following graph shows the contribution of each technology in the provision of daily, weekly and annual flexibility needs in Option (III).

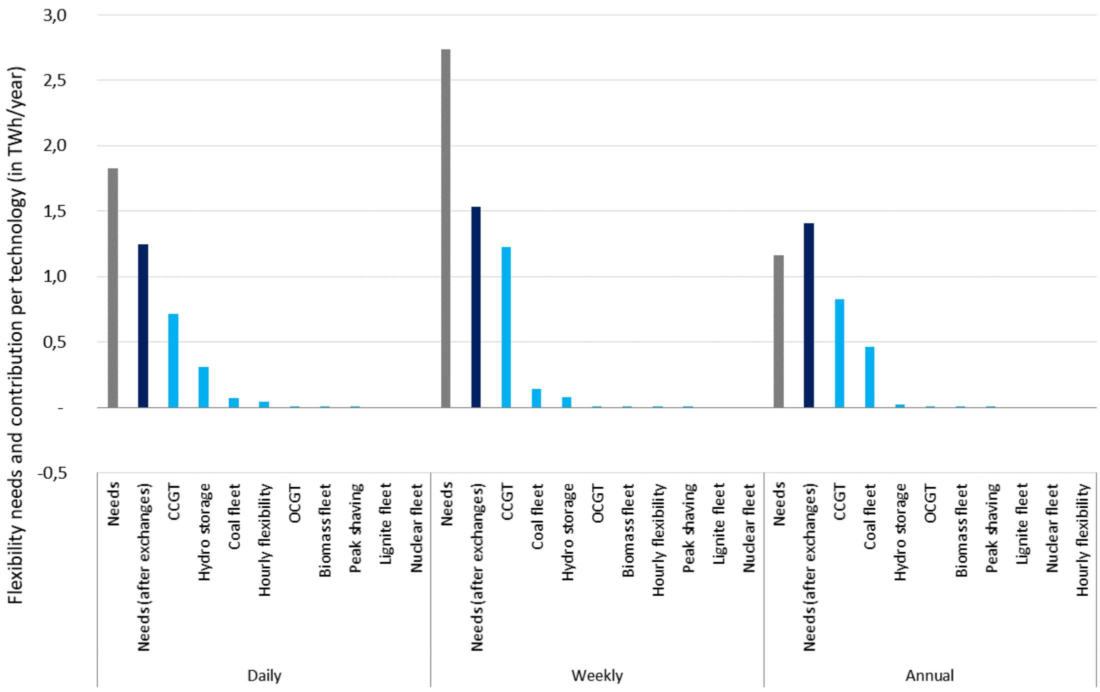

Figure 95: Contribution to flexibility needs per technology in Option (III)

The following graph shows the contribution of each technology to sub-hourly flexibility needs (i.e. participation in reserve procurement) in Option (III).

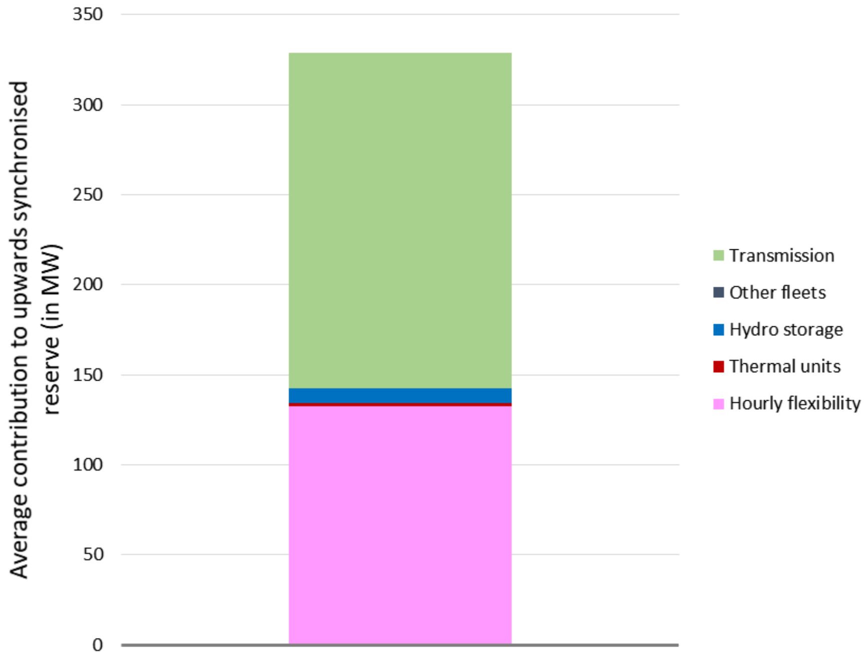

Figure 96: Contribution to upward synchronised reserve

Social welfare

The following table shows the evolution of the national social welfare between Option (II) and Option (I), and between Option (III) and Option (I), expressed in M€ per year.

The social welfare is defined as the sum of the producer surplus (driven by the difference between the market price and the variable generation cost), the consumer surplus (driven by the difference between what consumers would be ready to pay for electricity and the market price) and half the congestion rents (the revenues captured by interconnectors by exploiting the price difference between two zones).

The figures below do not take into account the savings in terms of investment costs, as these savings could be split between all the countries that have a common interest in a given project. At the EU28 level, compared to Option (I), these savings correspond to 150 M€ in Option (II) and to 210 M€ in Option (III).

	Evolution of social welfare (in M€ per year)
From Option (I) to Option (II)	+ 36 M€/y
From Option (I) to Option (III)	+ 64 M€/y

Table 54 - Evolution of social welfare

B.15 Italy

Scenario description and flexibility needs

The following tables provide information related to the assumptions inherited from the PRIMES EUCO30 scenario.

	EUCO30
Power demand (in TWh/y)	318.2
Variable RES generation (in TWh/y)	83.5
of which wind onshore	*31.4*
of which wind offshore	*0.0*
of which PV	*52.1*

Table 55 - Demand and variable RES generation

Baseload and mid-merit capacities	EUCO30
Nuclear (in GW)	0.00
Coal (in GW)	5.10
Lignite (in GW)	0.00

Table 56 - Baseload and mid-merit capacities

The following graph presents the trajectory of flexibility needs over the 2020-2030 period.

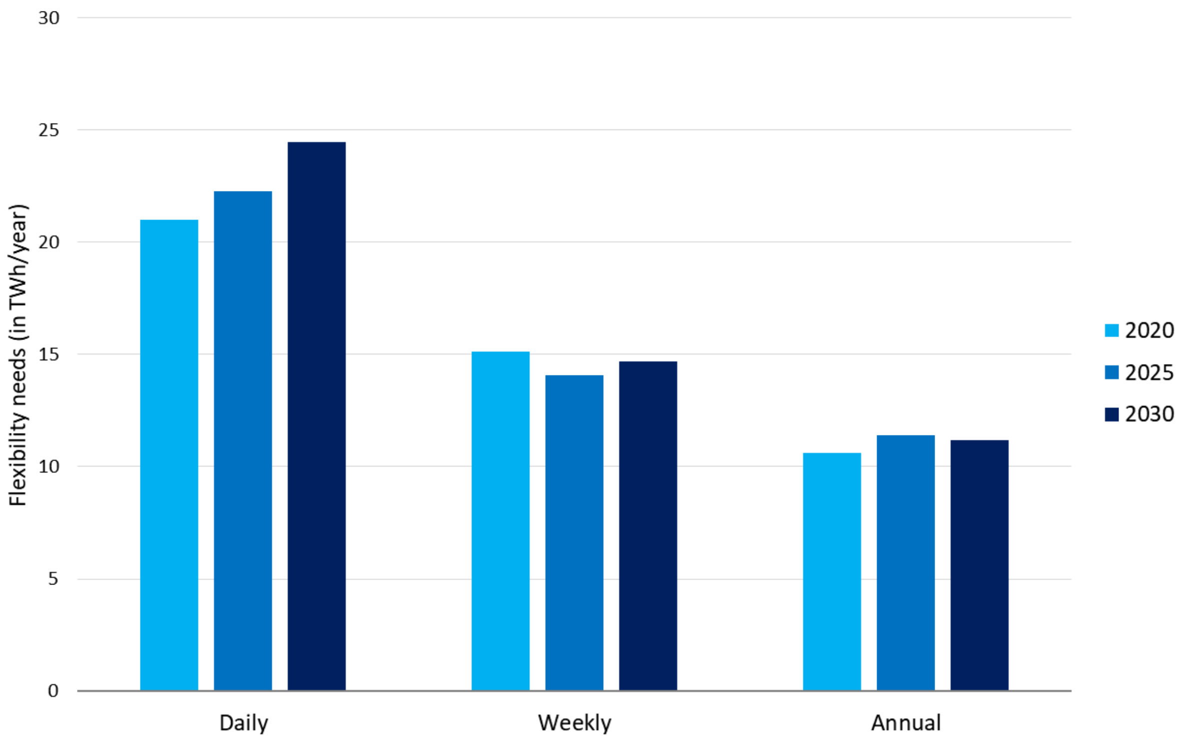

Figure 97 - Flexibility needs for 2020, 2025 and 2030

Flexibility portfolio

The following graph presents the potential for demand-response, storage and interconnectors, and the way these potentials are exploited in Options (II) and (III). Moreover, no batteries are found to be installed.

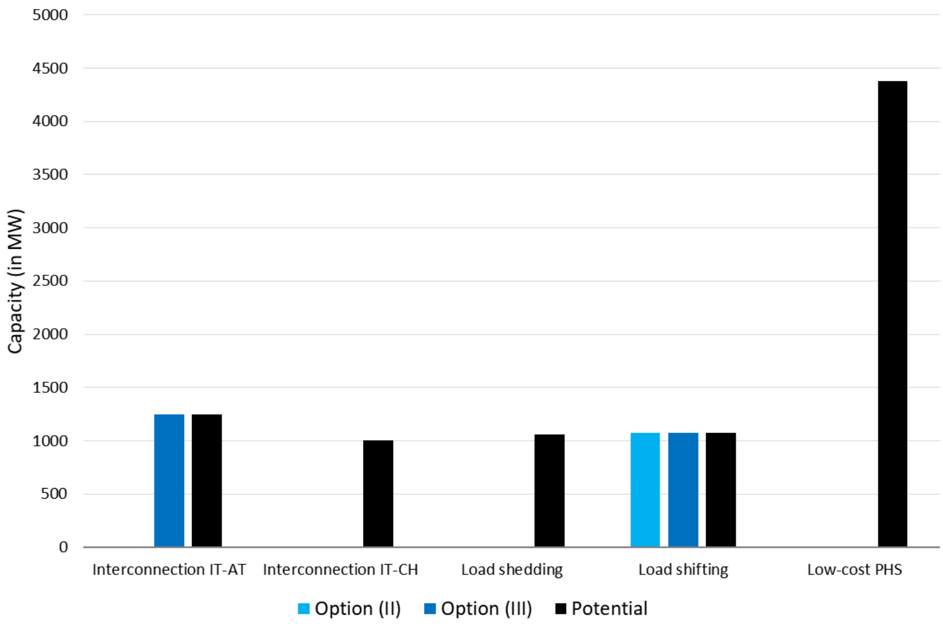

Figure 98 - Potential for flexibility solutions and installed capacities in Options (II) and (III)

Provision of flexibility

The following graph shows the contribution of each technology in the provision of daily, weekly and annual flexibility needs in Option (III).

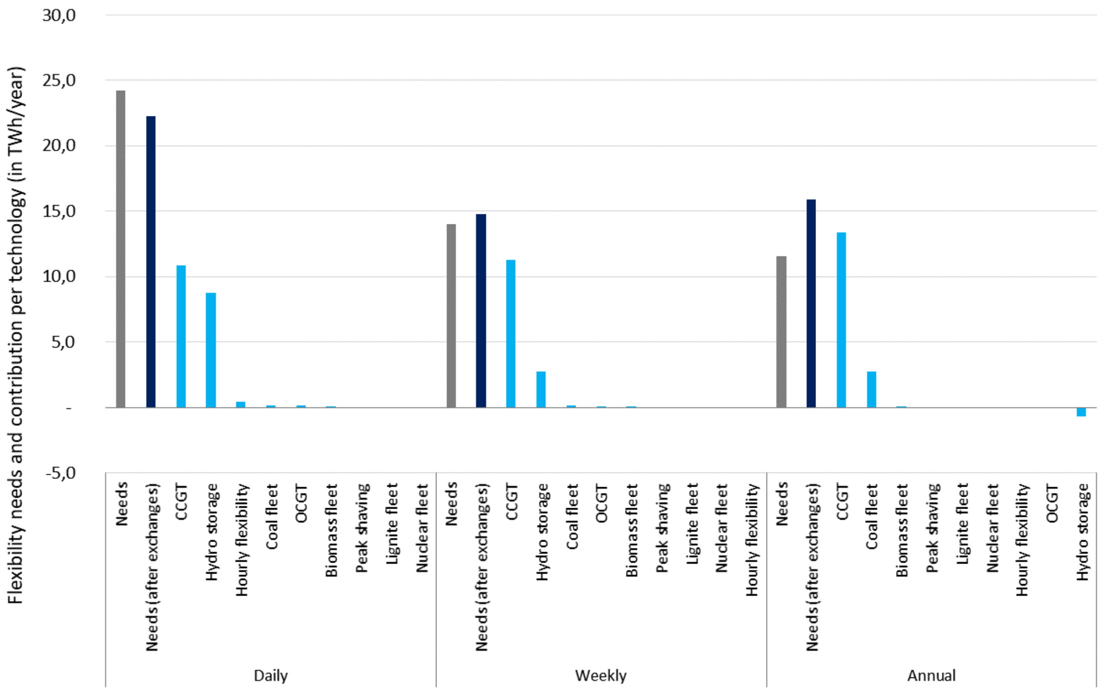

Figure 99: Contribution to flexibility needs per technology in Option (III)

The following graph shows the contribution of each technology to sub-hourly flexibility needs (i.e. participation in reserve procurement) in Option (III).

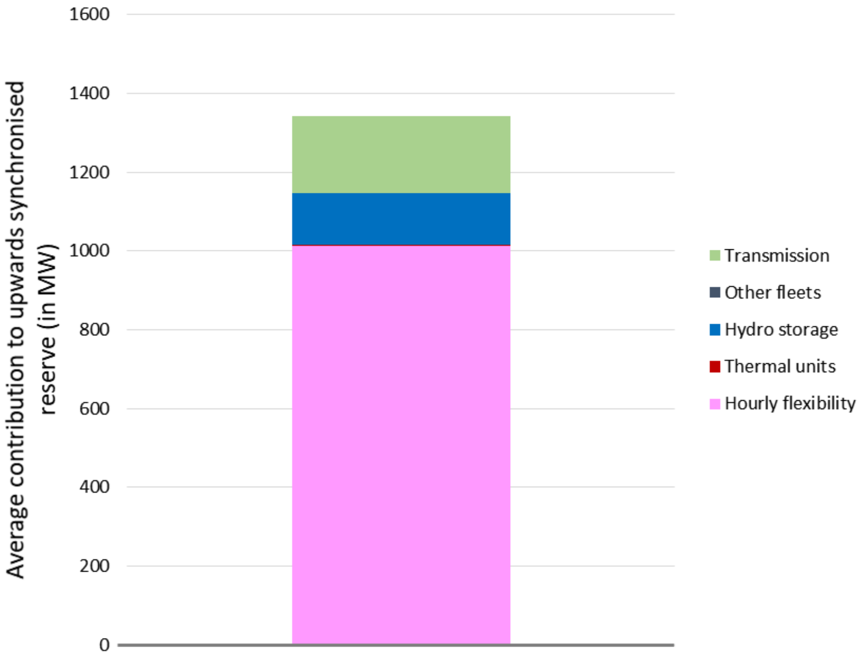

Figure 100: Contribution to upward synchronised reserve

Social welfare

The following table shows the evolution of the national social welfare between Option (II) and Option (I), and between Option (III) and Option (I), expressed in M€ per year.

The social welfare is defined as the sum of the producer surplus (driven by the difference between the market price and the variable generation cost), the consumer surplus (driven by the difference between what consumers would be ready to pay for electricity and the market price) and half the congestion rents (the revenues captured by interconnectors by exploiting the price difference between two zones).

The figures below do not take into account the savings in terms of investment costs, as these savings could be split between all the countries that have a common interest in a given project. At the EU28 level, compared to Option (I), these savings correspond to 150 M€ in Option (II) and to 210 M€ in Option (III).

	Evolution of social welfare (in M€ per year)
From Option (I) to Option (II)	+ 56 M€/y
From Option (I) to Option (III)	- 130 M€/y

Table 57 - Evolution of social welfare

B.16 Latvia

Scenario description and flexibility needs

The following tables provide information related to the assumptions inherited from the PRIMES EUCO30 scenario.

	EUCO30
Power demand (in TWh/y)	8.9
Variable RES generation (in TWh/y)	1.4
of which wind onshore	*1.3*
of which wind offshore	*0.2*
of which PV	*0.0*

Table 58 - Demand and variable RES generation

Baseload and mid-merit capacities	EUCO30
Nuclear (in GW)	0.00
Coal (in GW)	0.02
Lignite (in GW)	0.00

Table 59 - Baseload and mid-merit capacities

The following graph presents the trajectory of flexibility needs over the 2020-2030 period.

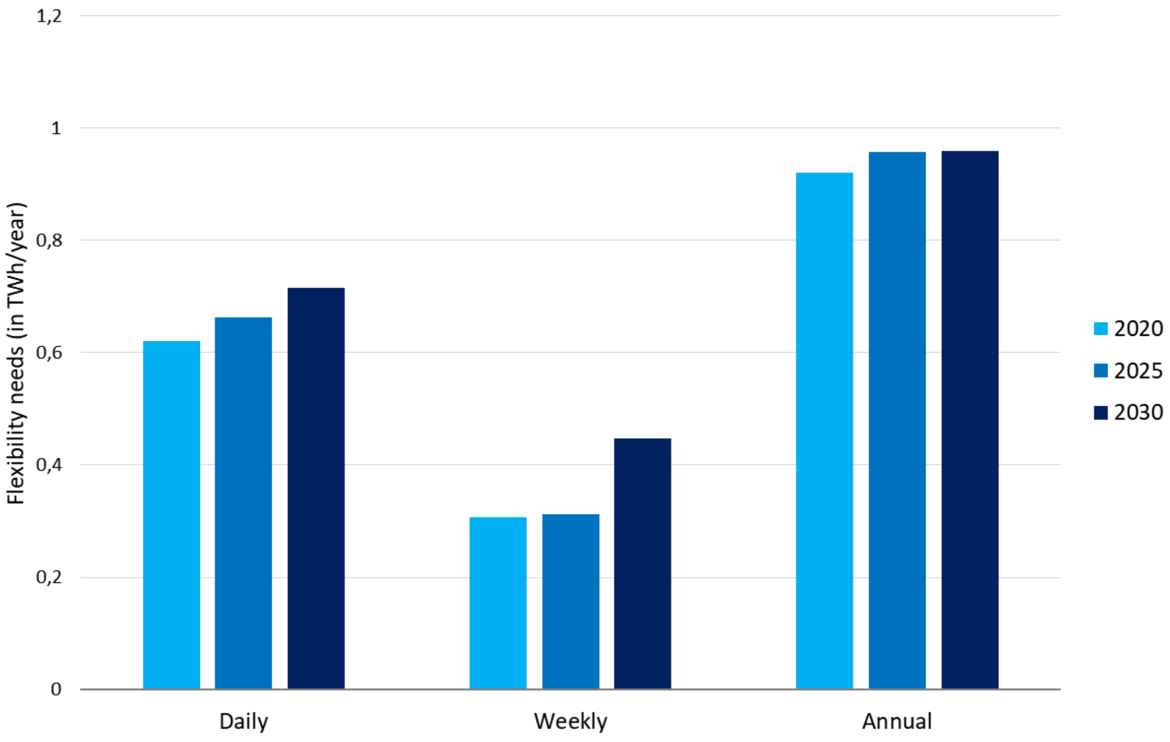

Figure 101 - Flexibility needs for 2020, 2025 and 2030

Flexibility portfolio

The following graph presents the potential for demand-response, storage and interconnectors, and the way these potentials are exploited in Options (II) and (III). Moreover, 40 MW of batteries are found to be installed in Options (II) and (III).

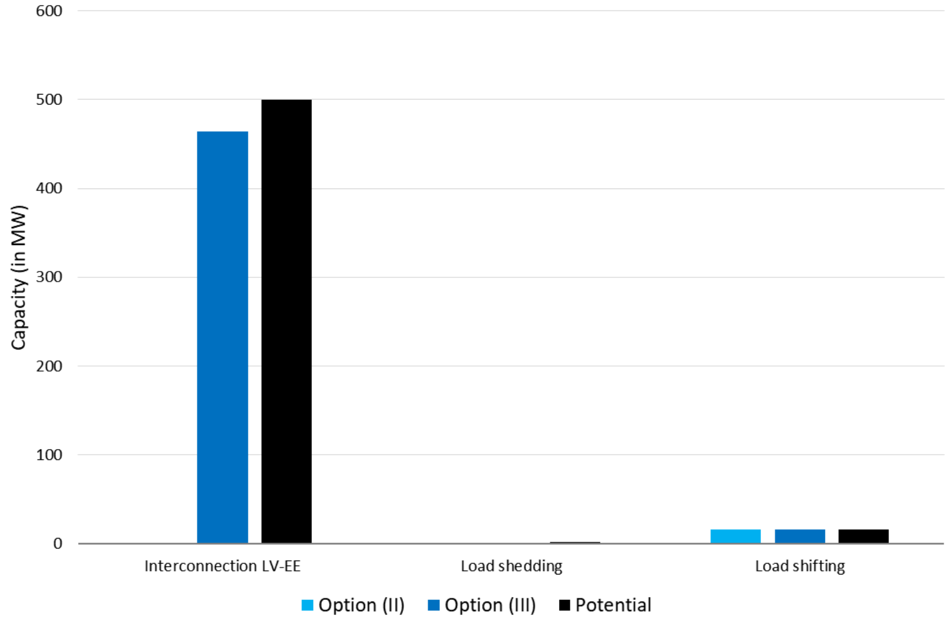

Figure 102 - Potential for flexibility solutions and installed capacities in Options (II) and (III)

Provision of flexibility

The following graph shows the contribution of each technology in the provision of daily, weekly and annual flexibility needs in Option (III).

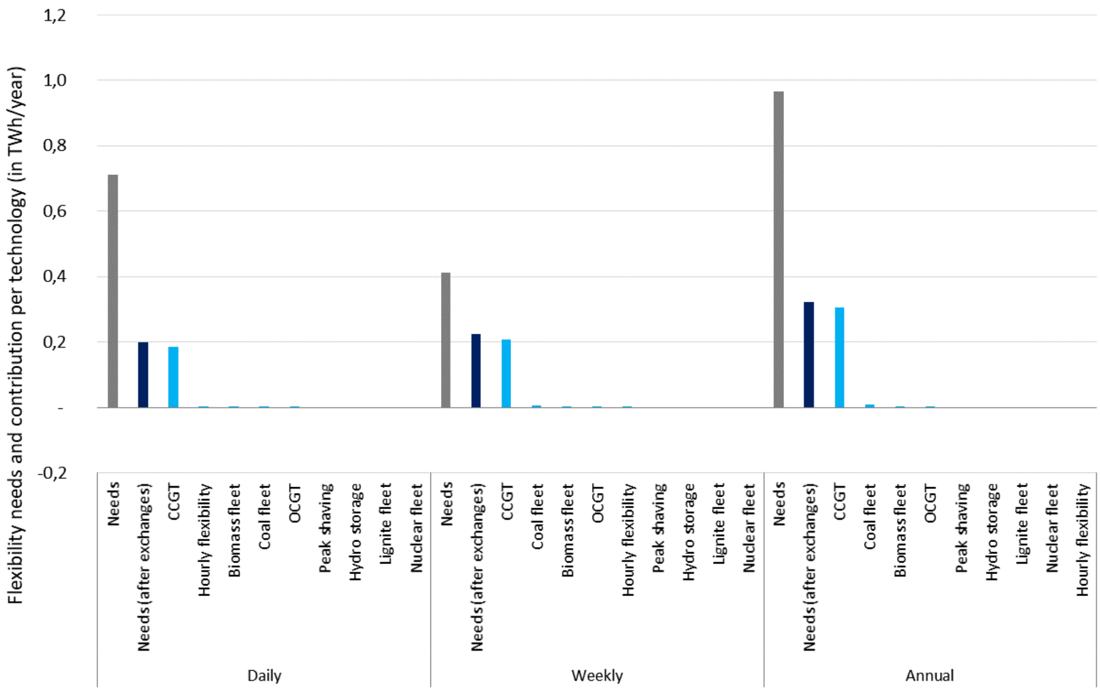

Figure 103: Contribution to flexibility needs per technology in Option (III)

The following graph shows the contribution of each technology to sub-hourly flexibility needs (i.e. participation in reserve procurement) in Option (III).

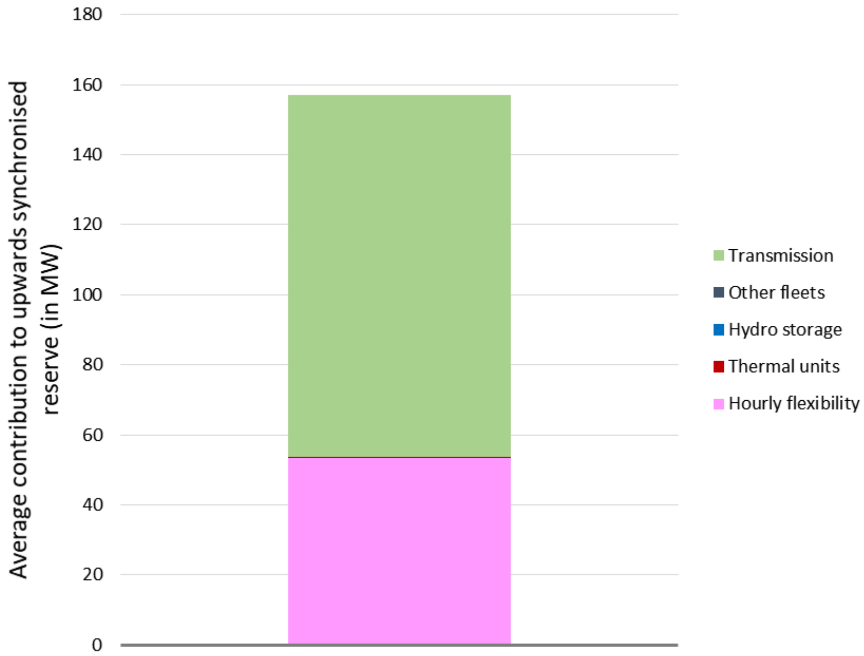

Figure 104: Contribution to upward synchronised reserve

Social welfare

The following table shows the evolution of the national social welfare between Option (II) and Option (I), and between Option (III) and Option (I), expressed in M€ per year.

The social welfare is defined as the sum of the producer surplus (driven by the difference between the market price and the variable generation cost), the consumer surplus (driven by the difference between what consumers would be ready to pay for electricity and the market price) and half the congestion rents (the revenues captured by interconnectors by exploiting the price difference between two zones).

The figures below do not take into account the savings in terms of investment costs, as these savings could be split between all the countries that have a common interest in a given project. At the EU28 level, compared to Option (I), these savings correspond to 150 M€ in Option (II) and to 210 M€ in Option (III).

	Evolution of social welfare (in M€ per year)
From Option (I) to Option (II)	+ 2 M€/y
From Option (I) to Option (III)	- 7 M€/y

Table 60 - Evolution of social welfare

B.17 Lithuania

Scenario description and flexibility needs

The following tables provide information related to the assumptions inherited from the PRIMES EUCO30 scenario.

	EUCO30
Power demand (in TWh/y)	11.5
Variable RES generation (in TWh/y)	2.0
of which wind onshore	*1.9*
of which wind offshore	*0.0*
of which PV	*0.1*

Table 61 - Demand and variable RES generation

Baseload and mid-merit capacities	EUCO30
Nuclear (in GW)	1.12
Coal (in GW)	0.00
Lignite (in GW)	0.00

Table 62 - Baseload and mid-merit capacities

The following graph presents the trajectory of flexibility needs over the 2020-2030 period.

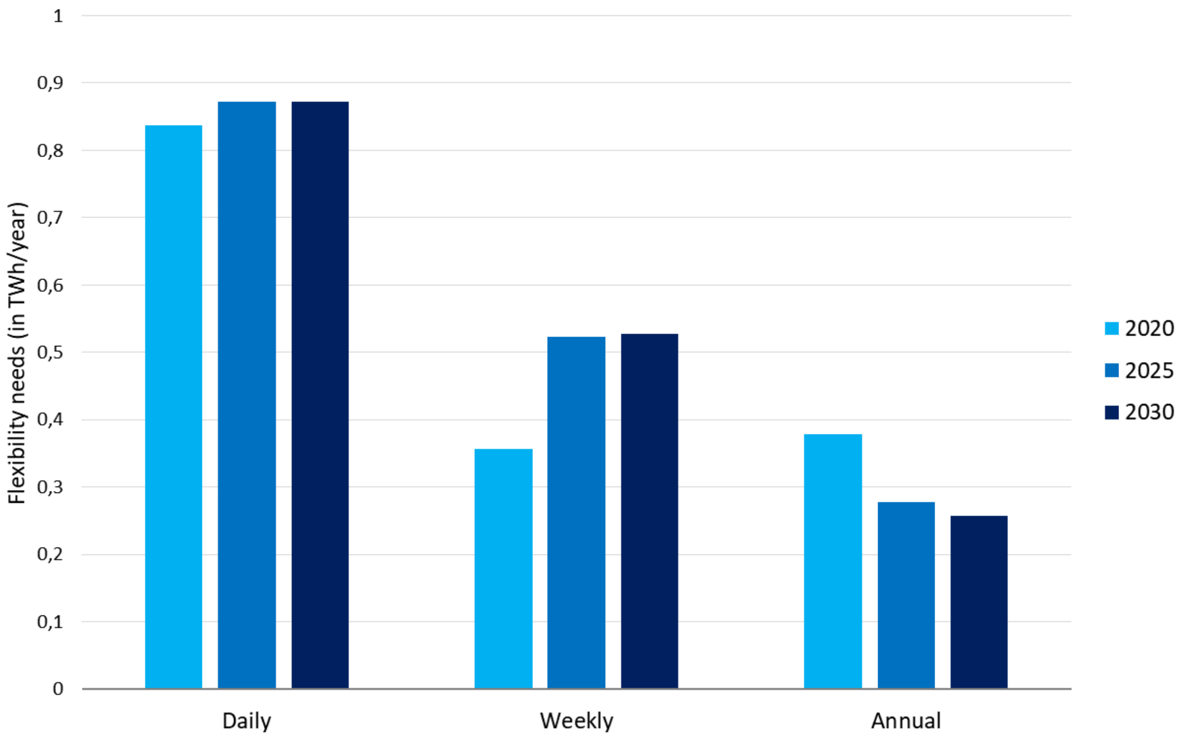

Figure 105 - Flexibility needs for 2020, 2025 and 2030

Flexibility portfolio

The following graph presents the potential for demand-response, storage and interconnectors, and the way these potentials are exploited in Options (II) and (III). Moreover, 50 MW of batteries are found to be installed in Options (II) and (III).

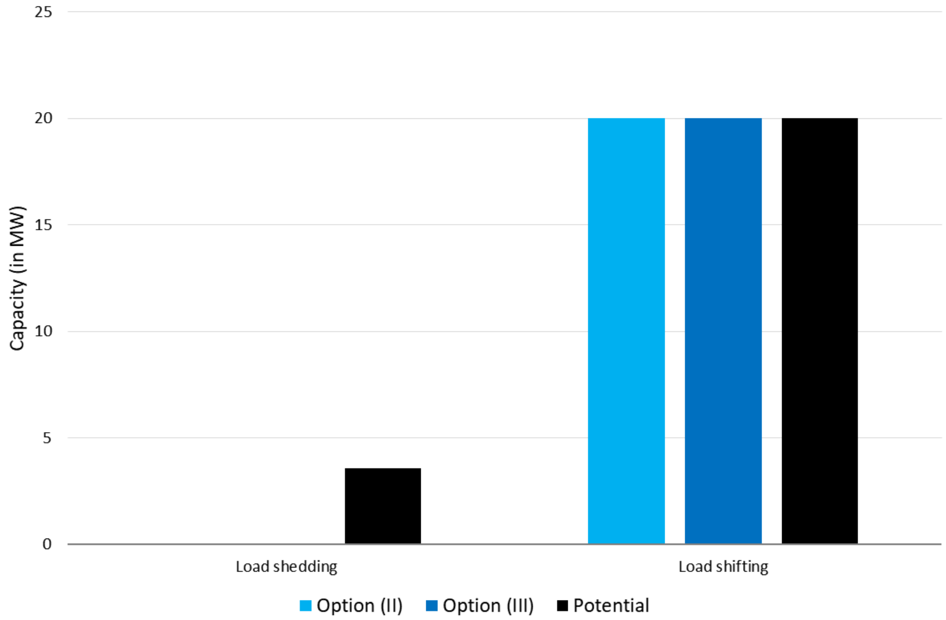

Figure 106 - Potential for flexibility solutions and installed capacities in Options (II) and (III)

Provision of flexibility

The following graph shows the contribution of each technology in the provision of daily, weekly and annual flexibility needs in Option (III).

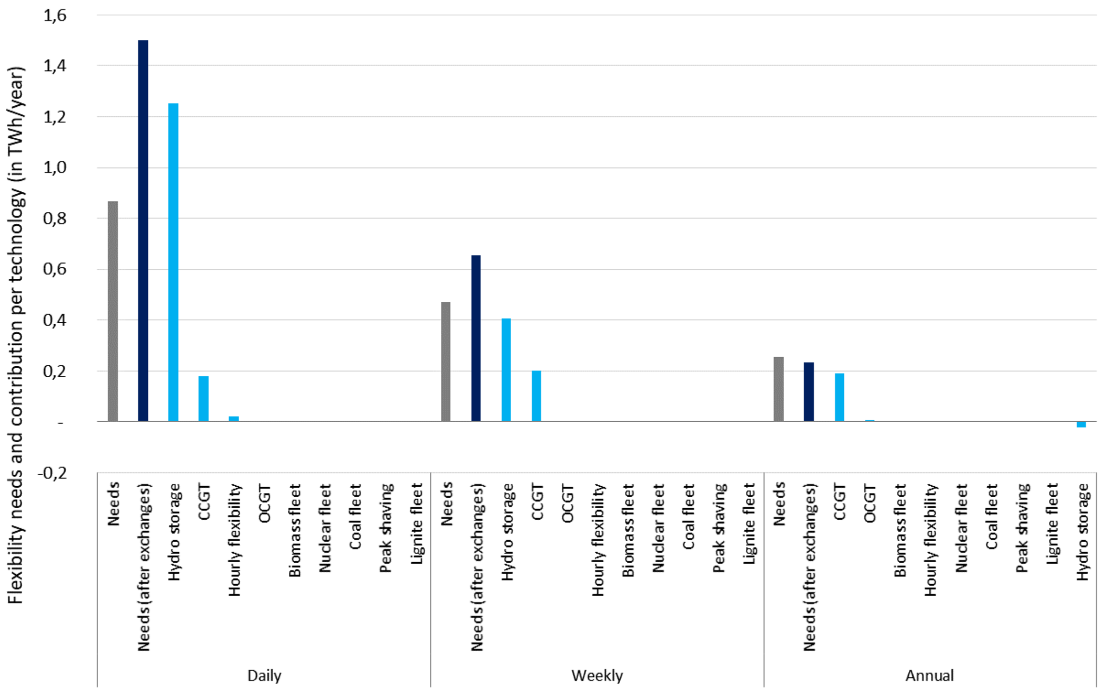

Figure 107: Contribution to flexibility needs per technology in Option (III)

The following graph shows the contribution of each technology to sub-hourly flexibility needs (i.e. participation in reserve procurement) in Option (III).

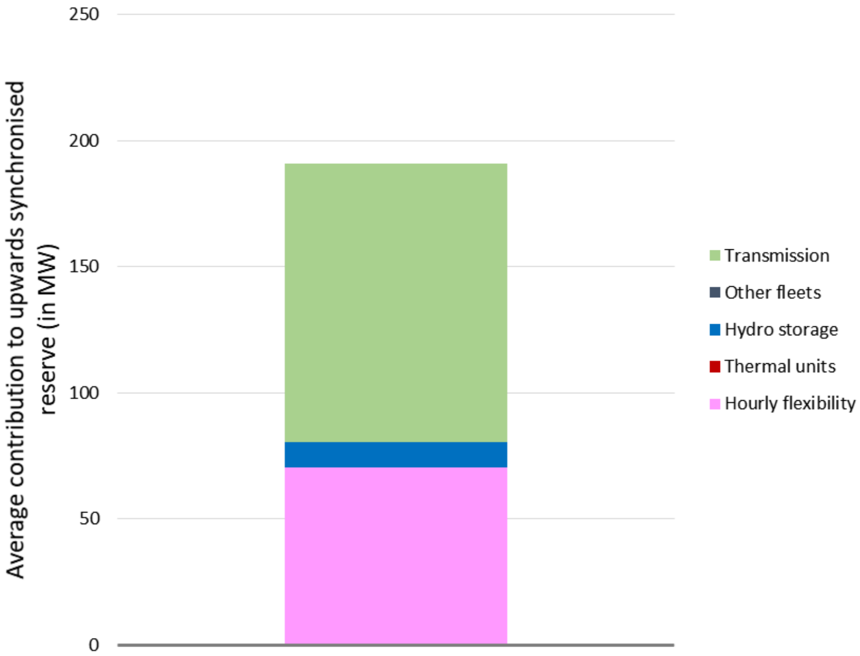

Figure 108: Contribution to upward synchronised reserve

Social welfare

The following table shows the evolution of the national social welfare between Option (II) and Option (I), and between Option (III) and Option (I), expressed in M€ per year.

The social welfare is defined as the sum of the producer surplus (driven by the difference between the market price and the variable generation cost), the consumer surplus (driven by the difference between what consumers would be ready to pay for electricity and the market price) and half the congestion rents (the revenues captured by interconnectors by exploiting the price difference between two zones).

The figures below do not take into account the savings in terms of investment costs, as these savings could be split between all the countries that have a common interest in a given project. At the EU28 level, compared to Option (I), these savings correspond to 150 M€ in Option (II) and to 210 M€ in Option (III).

	Evolution of social welfare (in M€ per year)
From Option (I) to Option (II)	- 6 M€/y
From Option (I) to Option (III)	No impact

Table 63 - Evolution of social welfare

B.18 Luxembourg

Scenario description and flexibility needs

The following tables provide information related to the assumptions inherited from the PRIMES EUCO30 scenario.

	EUCO30
Power demand (in TWh/y)	8.2
Variable RES generation (in TWh/y)	0.9
of which wind onshore	*0.6*
of which wind offshore	*0.0*
of which PV	*0.3*

Table 64 - Demand and variable RES generation

Baseload and mid-merit capacities	EUCO30
Nuclear (in GW)	0.00
Coal (in GW)	0.00
Lignite (in GW)	0.00

Table 65 - Baseload and mid-merit capacities

The following graph presents the trajectory of flexibility needs over the 2020-2030 period.

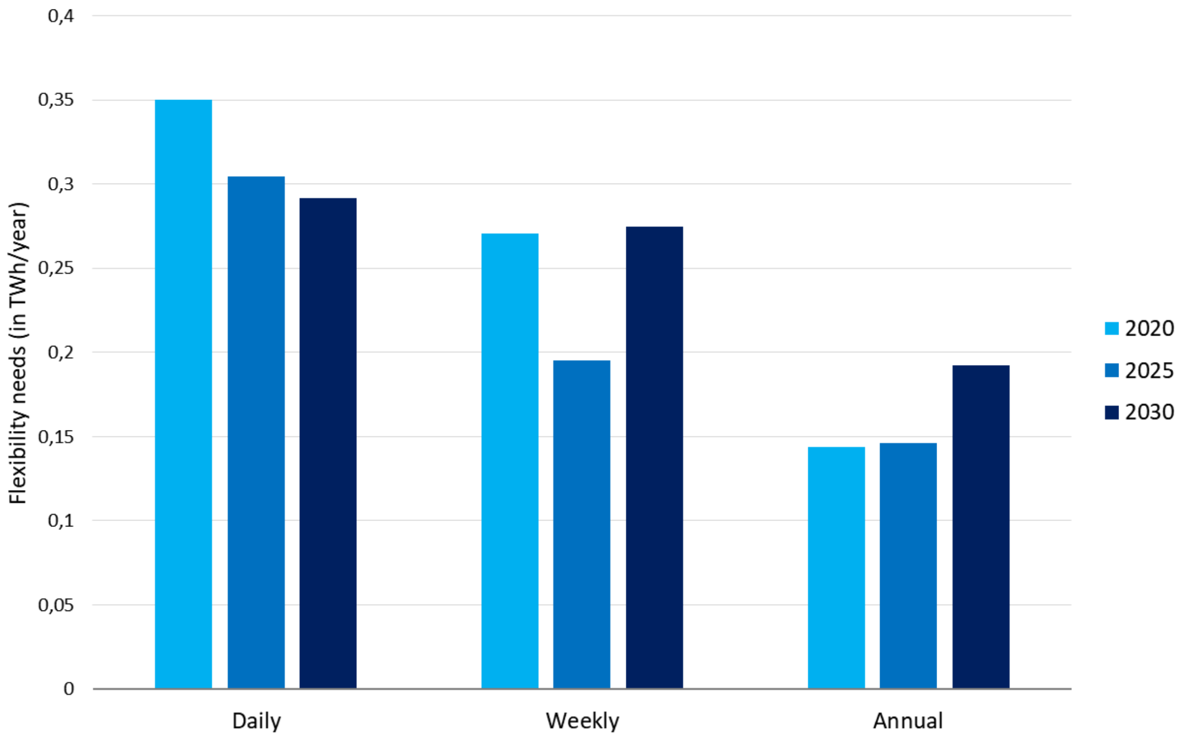

Figure 109 - Flexibility needs for 2020, 2025 and 2030

Flexibility portfolio

The following graph presents the potential for demand-response, storage and interconnectors, and the way these potentials are exploited in Options (II) and (III). Moreover, no batteries are found to be installed.

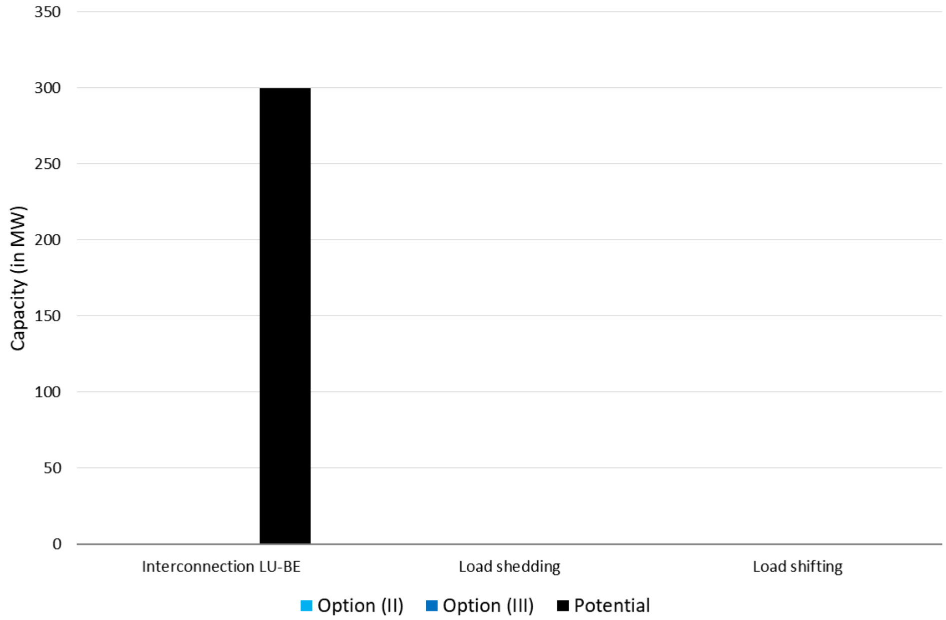

Figure 110 - Potential for flexibility solutions and installed capacities in Options (II) and (III)

Provision of flexibility

The following graph shows the contribution of each technology in the provision of daily, weekly and annual flexibility needs in Option (III).

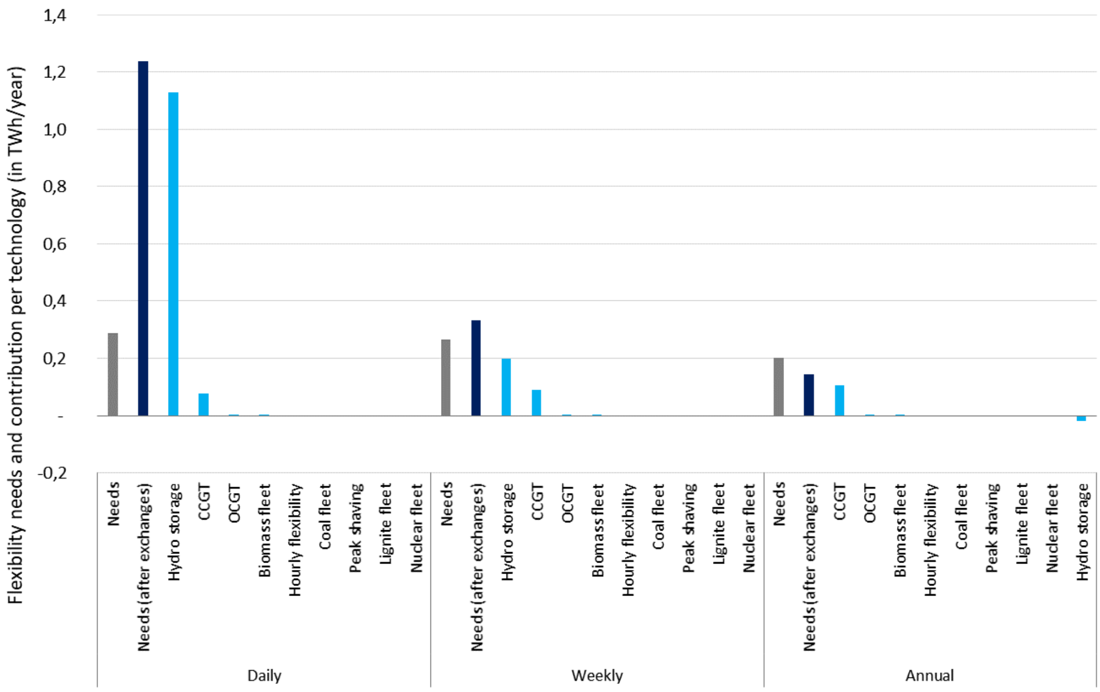

Figure 111: Contribution to flexibility needs per technology in Option (III)

Due to the lack of data, reserve procurement has not been modelled for this Member State.

Social welfare

The following table shows the evolution of the national social welfare between Option (II) and Option (I), and between Option (III) and Option (I), expressed in M€ per year.

The social welfare is defined as the sum of the producer surplus (driven by the difference between the market price and the variable generation cost), the consumer surplus (driven by the difference between what consumers would be ready to pay for electricity and the market price) and half the congestion rents (the revenues captured by interconnectors by exploiting the price difference between two zones).

The figures below do not take into account the savings in terms of investment costs, as these savings could be split between all the countries that have a common interest in a given project. At the EU28 level, compared to Option (I), these savings correspond to 150 M€ in Option (II) and to 210 M€ in Option (III).

	Evolution of social welfare (in M€ per year)
From Option (I) to Option (II)	- 13 M€/y
From Option (I) to Option (III)	- 11 M€/y

Table 66 - Evolution of social welfare

B.19 Malta

Scenario description and flexibility needs

The following tables provide information related to the assumptions inherited from the PRIMES EUCO30 scenario.

	EUCO30
Power demand (in TWh/y)	2.6
Variable RES generation (in TWh/y)	0.5
of which wind onshore	*0.0*
of which wind offshore	*0.0*
of which PV	*0.5*

Table 67 - Demand and variable RES generation

Baseload and mid-merit capacities	EUCO30
Nuclear (in GW)	0.00
Coal (in GW)	0.00
Lignite (in GW)	0.00

Table 68 - Baseload and mid-merit capacities

The following graph presents the trajectory of flexibility needs over the 2020-2030 period.

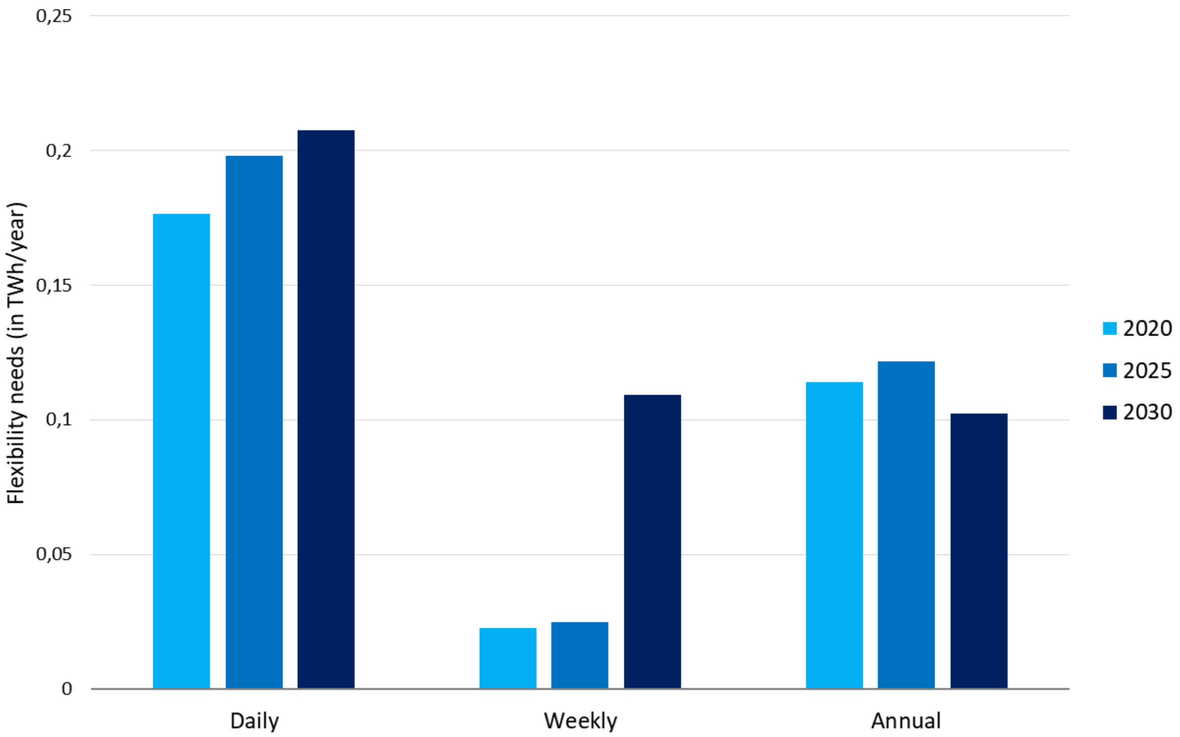

Figure 112 - Flexibility needs for 2020, 2025 and 2030

Flexibility portfolio

In this modelling exercise, there is no potential for demand-response, storage and interconnectors in this Member State. No batteries are found to be installed.

Provision of flexibility

The following graph shows the contribution of each technology in the provision of daily, weekly and annual flexibility needs in Option (III).

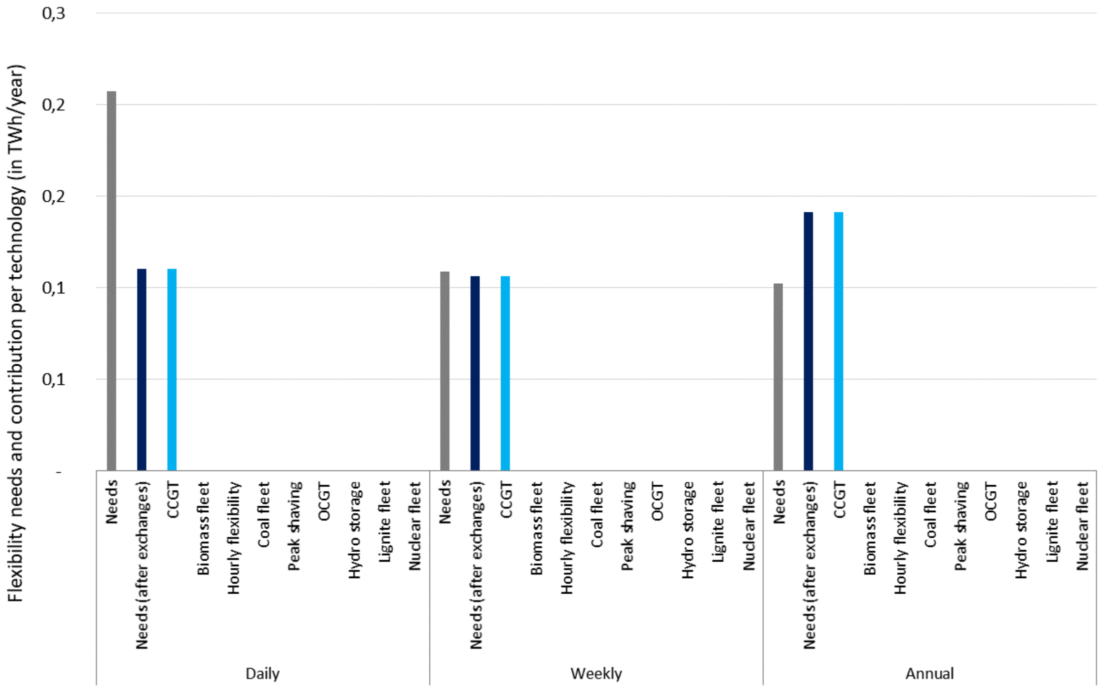

Figure 113: Contribution to flexibility needs per technology in Option (III)

Due to the lack of data, reserve procurement has not been modelled for this Member State.

Social welfare

The following table shows the evolution of the national social welfare between Option (II) and Option (I), and between Option (III) and Option (I), expressed in M€ per year.

The social welfare is defined as the sum of the producer surplus (driven by the difference between the market price and the variable generation cost), the consumer surplus (driven by the difference between what consumers would be ready to pay for electricity and the market price) and half the congestion rents (the revenues captured by interconnectors by exploiting the price difference between two zones).

The figures below do not take into account the savings in terms of investment costs, as these savings could be split between all the countries that have a common interest in a given project. At the EU28 level, compared to Option (I), these savings correspond to 150 M€ in Option (II) and to 210 M€ in Option (III).

	Evolution of social welfare (in M€ per year)
From Option (I) to Option (II)	+ 0.4 M€/y
From Option (I) to Option (III)	+ 0.4 M€/y

Table 69 - Evolution of social welfare

B.20 The Netherlands

Scenario description and flexibility needs

The following tables provide information related to the assumptions inherited from the PRIMES EUCO30 scenario.

	EUCO30
Power demand (in TWh/y)	118.6
Variable RES generation (in TWh/y)	33.4
of which wind onshore	*19.1*
of which wind offshore	*9.0*
of which PV	*5.3*

Table 70 - Demand and variable RES generation

Baseload and mid-merit capacities	EUCO30
Nuclear (in GW)	0.49
Coal (in GW)	4.43
Lignite (in GW)	0.00

Table 71 - Baseload and mid-merit capacities

The following graph presents the trajectory of flexibility needs over the 2020-2030 period.

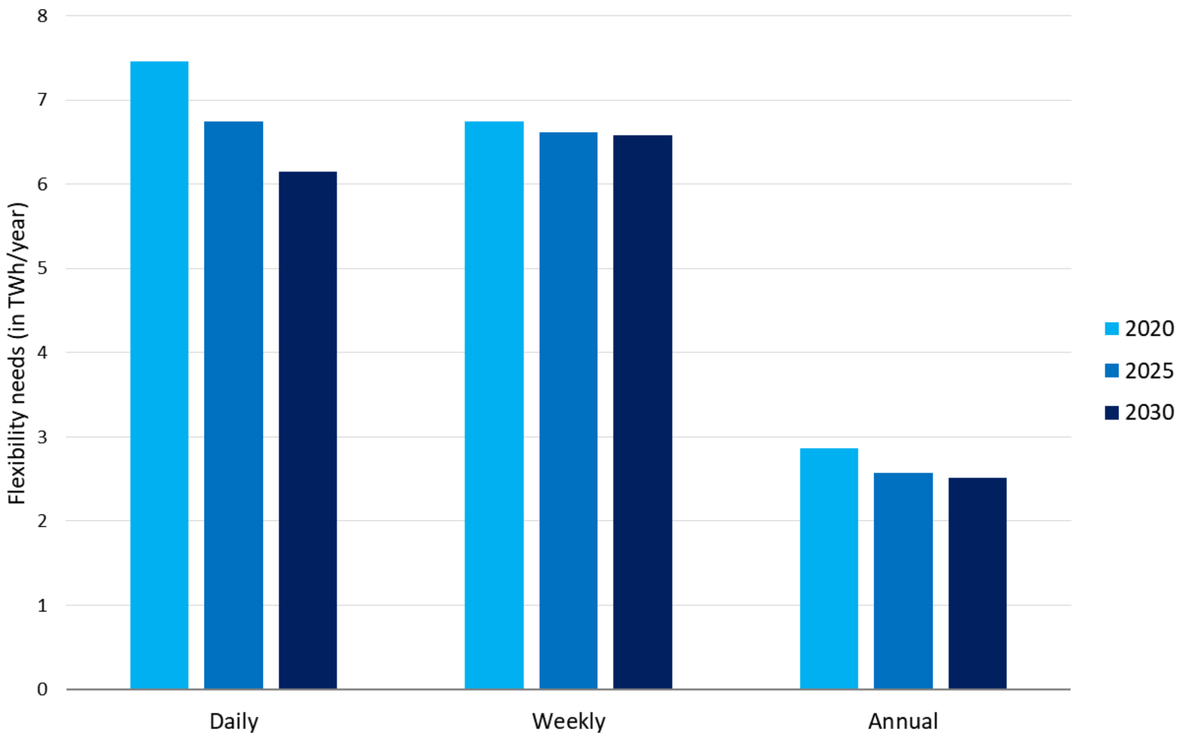

Figure 114 - Flexibility needs for 2020, 2025 and 2030

Flexibility portfolio

The following graph presents the potential for demand-response, storage and interconnectors, and the way these potentials are exploited in Options (II) and (III). Moreover, 30 MW of batteries are found to be installed in Options (II) and (III)

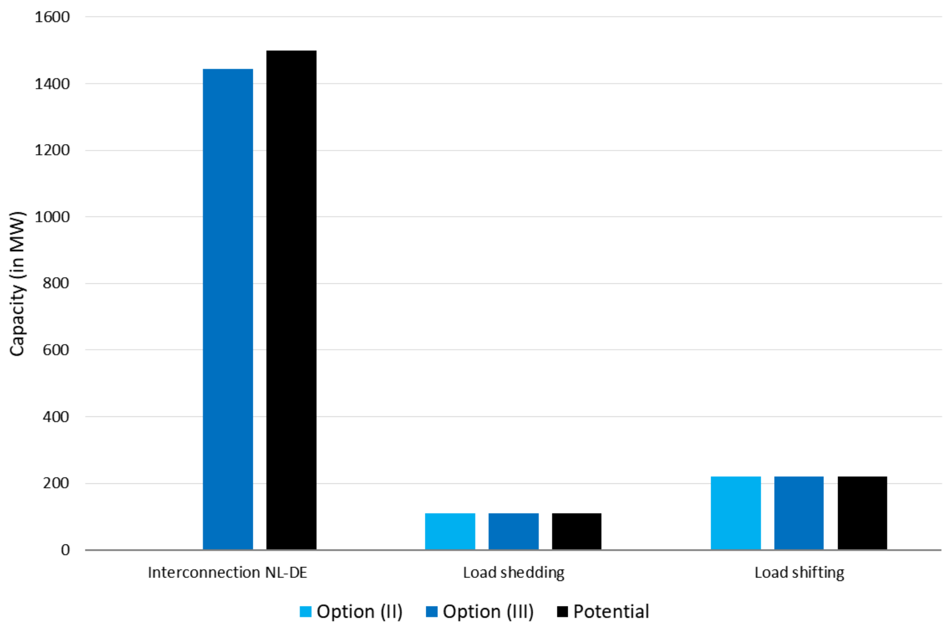

Figure 115 - Potential for flexibility solutions and installed capacities in Options (II) and (III)

Provision of flexibility

The following graph shows the contribution of each technology in the provision of daily, weekly and annual flexibility needs in Option (III).

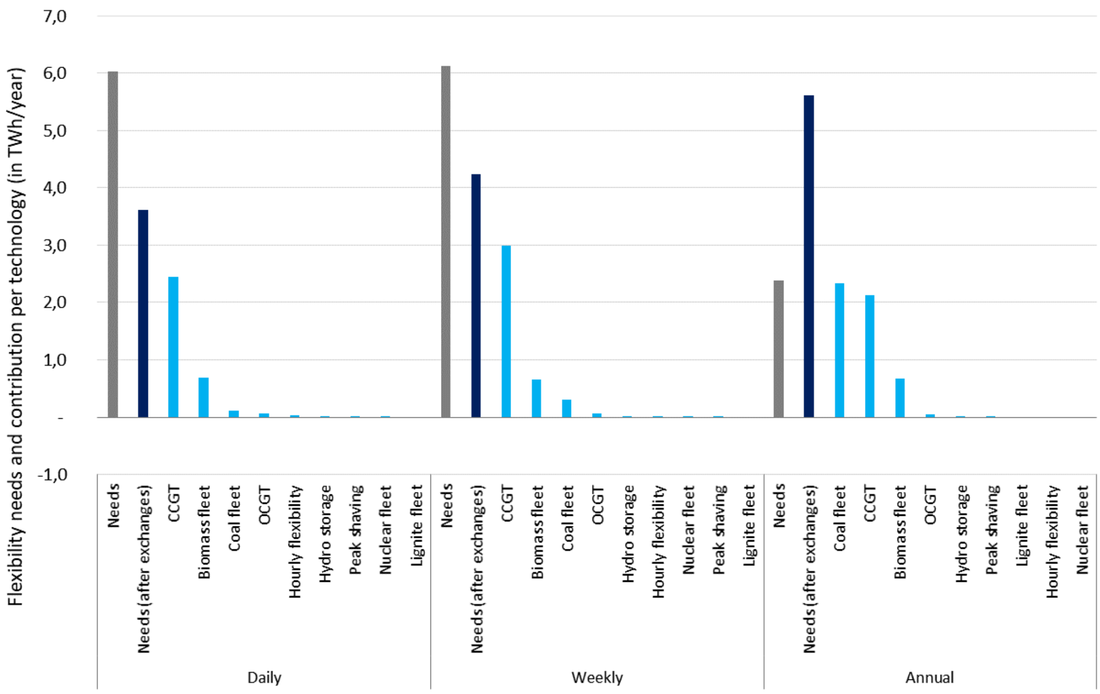

Figure 116: Contribution to flexibility needs per technology in Option (III)

The following graph shows the contribution of each technology to sub-hourly flexibility needs (i.e. participation in reserve procurement) in Option (III).

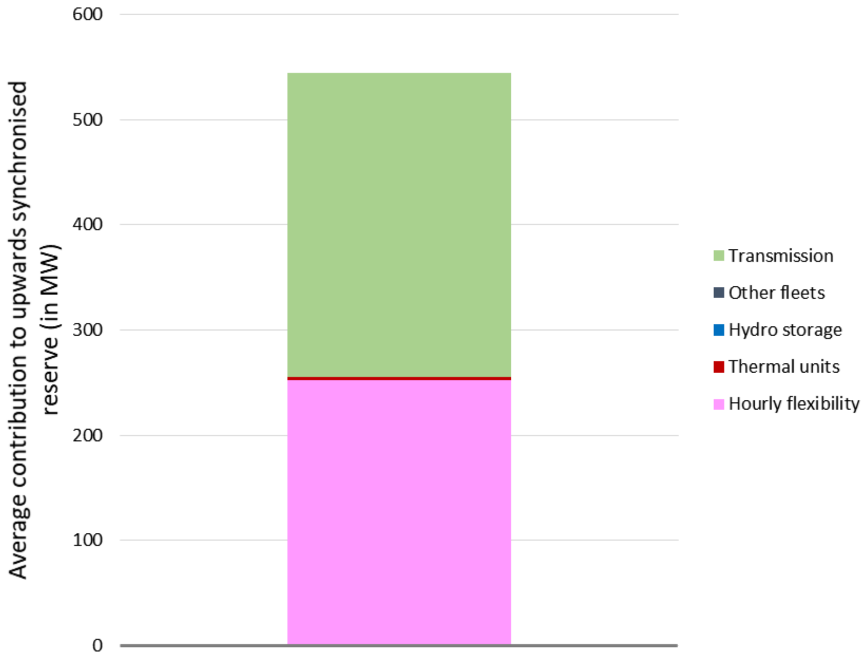

Figure 117: Contribution to upward synchronised reserve

Social welfare

The following table shows the evolution of the national social welfare between Option (II) and Option (I), and between Option (III) and Option (I), expressed in M€ per year.

The social welfare is defined as the sum of the producer surplus (driven by the difference between the market price and the variable generation cost), the consumer surplus (driven by the difference between what consumers would be ready to pay for electricity and the market price) and half the congestion rents (the revenues captured by interconnectors by exploiting the price difference between two zones).

The figures below do not take into account the savings in terms of investment costs, as these savings could be split between all the countries that have a common interest in a given project. At the EU28 level, compared to Option (I), these savings correspond to 150 M€ in Option (II) and to 210 M€ in Option (III).

	Evolution of social welfare (in M€ per year)
From Option (I) to Option (II)	+ 0.95 M€/y
From Option (I) to Option (III)	+ 41.00 M€/y

Table 72 - Evolution of social welfare

B.21 Poland

Scenario description and flexibility needs

The following tables provide information related to the assumptions inherited from the PRIMES EUCO30 scenario.

	EUCO30
Power demand (in TWh/y)	185.4
Variable RES generation (in TWh/y)	32.0
of which wind onshore	*28.5*
of which wind offshore	*2.5*
of which PV	*1.0*

Table 73 - Demand and variable RES generation

Baseload and mid-merit capacities	EUCO30
Nuclear (in GW)	0.00
Coal (in GW)	12.98
Lignite (in GW)	6.37

Table 74 - Baseload and mid-merit capacities

The following graph presents the trajectory of flexibility needs over the 2020-2030 period.

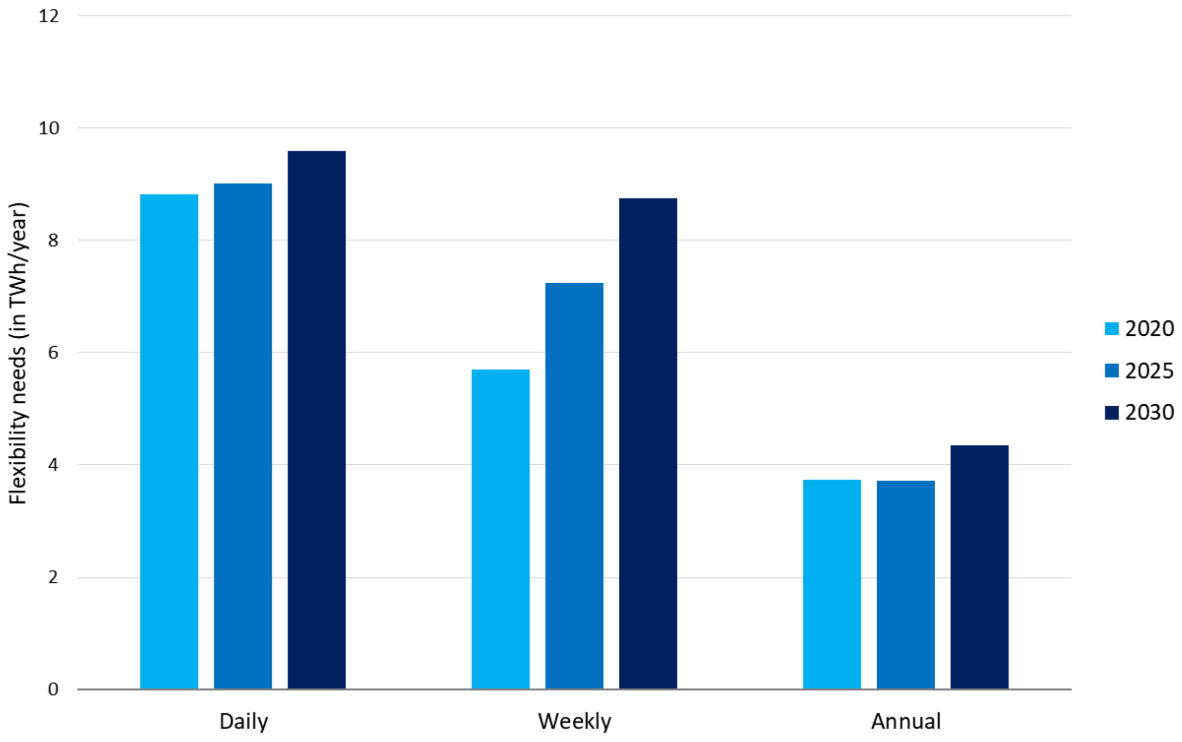

Figure 118 - Flexibility needs for 2020, 2025 and 2030

Flexibility portfolio

The following graph presents the potential for demand-response, storage and interconnectors, and the way these potentials are exploited in Options (II) and (III). Moreover, 10 MW of batteries are found to be installed in Options (II) and (III).

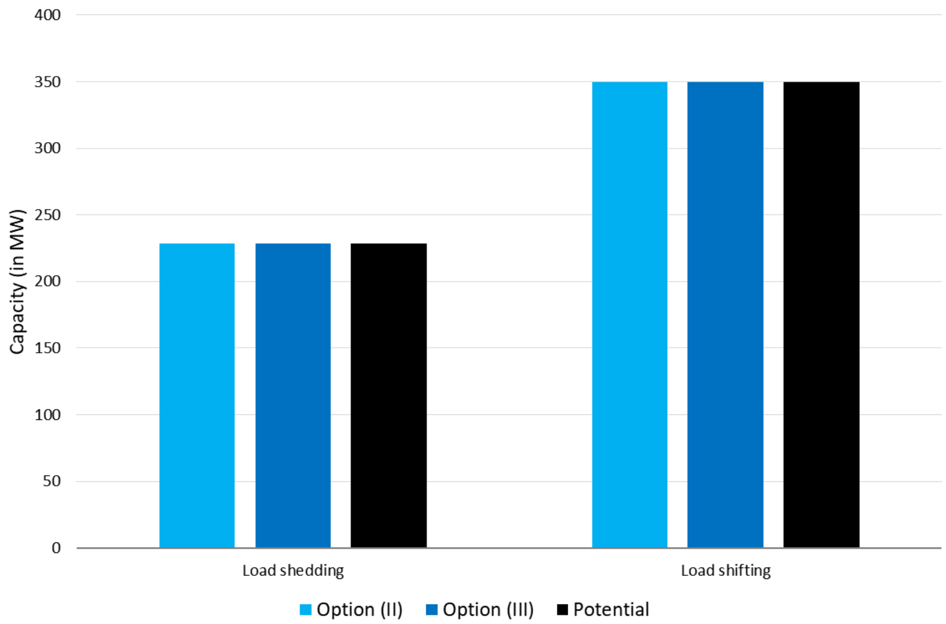

Figure 119 - Potential for flexibility solutions and installed capacities in Options (II) and (III)

Provision of flexibility

The following graph shows the contribution of each technology in the provision of daily, weekly and annual flexibility needs in Option (III).

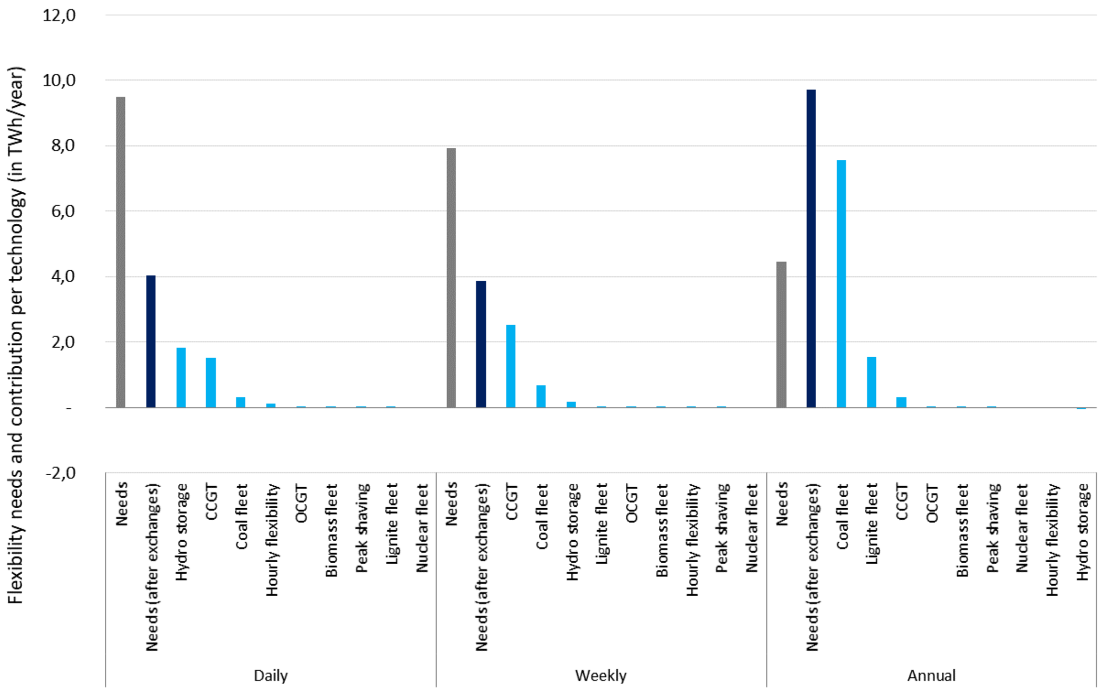

Figure 120: Contribution to flexibility needs per technology in Option (III)

The following graph shows the contribution of each technology to sub-hourly flexibility needs (i.e. participation in reserve procurement) in Option (III).

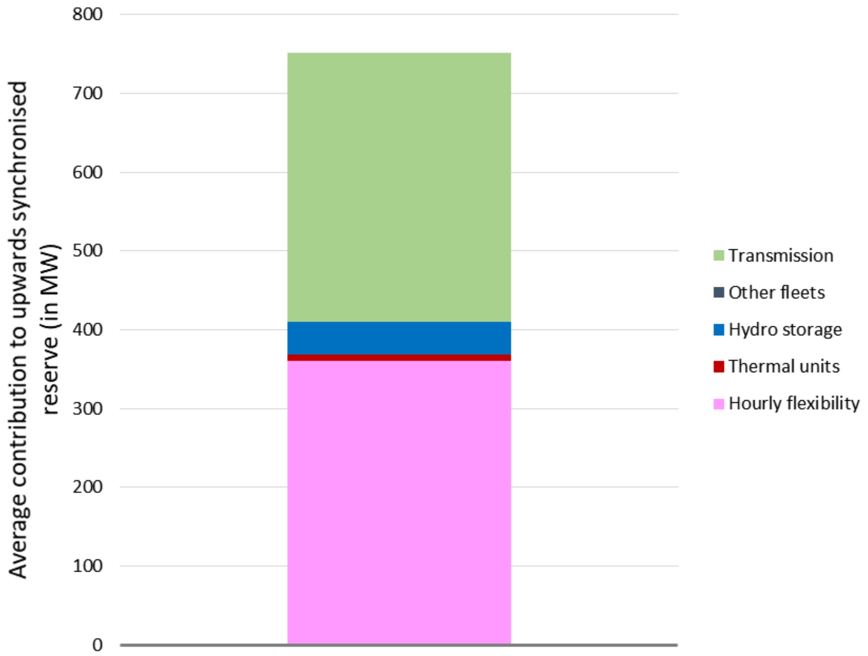

Figure 121: Contribution to upward synchronised reserve

Social welfare

The following table shows the evolution of the national social welfare between Option (II) and Option (I), and between Option (III) and Option (I), expressed in M€ per year.

The social welfare is defined as the sum of the producer surplus (driven by the difference between the market price and the variable generation cost), the consumer surplus (driven by the difference between what consumers would be ready to pay for electricity and the market price) and half the congestion rents (the revenues captured by interconnectors by exploiting the price difference between two zones).

The figures below do not take into account the savings in terms of investment costs, as these savings could be split between all the countries that have a common interest in a given project. At the EU28 level, compared to Option (I), these savings correspond to 150 M€ in Option (II) and to 210 M€ in Option (III).

	Evolution of social welfare (in M€ per year)
From Option (I) to Option (II)	+ 83 M€/y
From Option (I) to Option (III)	+ 52 M€/y

Table 75 - Evolution of social welfare

B.22 Portugal

Scenario description and flexibility needs

The following tables provide information related to the assumptions inherited from the PRIMES EUCO30 scenario.

	EUCO30
Power demand (in TWh/y)	49.6
Variable RES generation (in TWh/y)	20.8
of which wind onshore	*16.9*
of which wind offshore	*0.1*
of which PV	*3.9*

Table 76 - Demand and variable RES generation

Baseload and mid-merit capacities	EUCO30
Nuclear (in GW)	0.00
Coal (in GW)	0.00
Lignite (in GW)	0.00

Table 77 - Baseload and mid-merit capacities

The following graph presents the trajectory of flexibility needs over the 2020-2030 period.

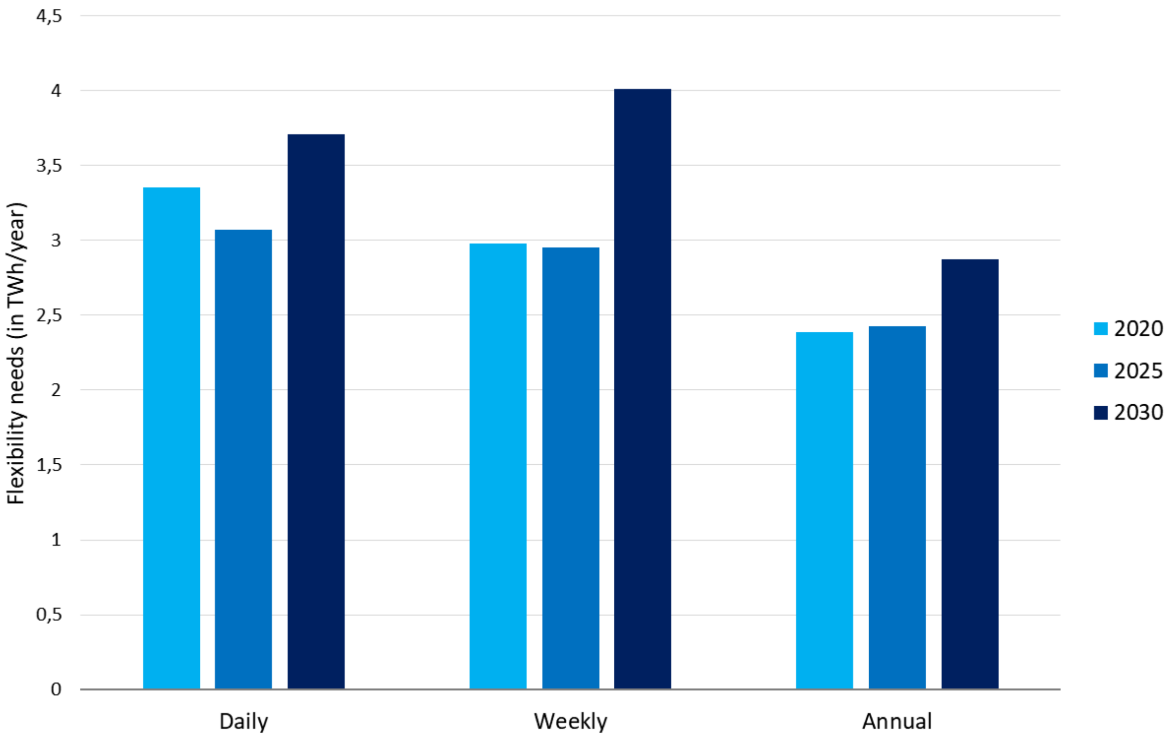

Figure 122 - Flexibility needs for 2020, 2025 and 2030

Flexibility portfolio

The following graph presents the potential for demand-response, storage and interconnectors, and the way these potentials are exploited in Options (II) and (III). Moreover, 30 MW of batteries are found to be installed in Option (II) and 40 MW in Option (III).

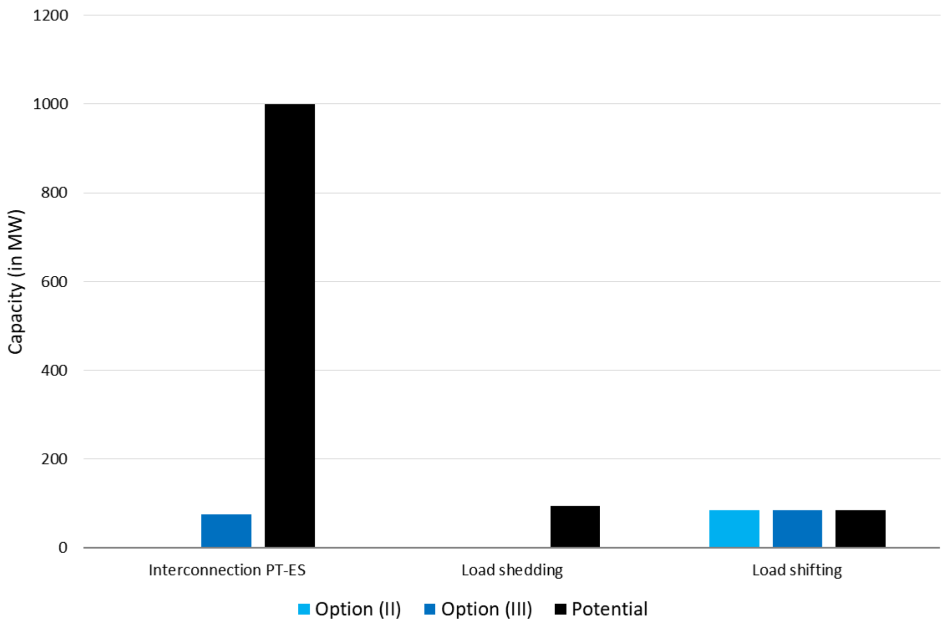

Figure 123 - Potential for flexibility solutions and installed capacities in Options (II) and (III)

Provision of flexibility

The following graph shows the contribution of each technology in the provision of daily, weekly and annual flexibility needs in Option (III).

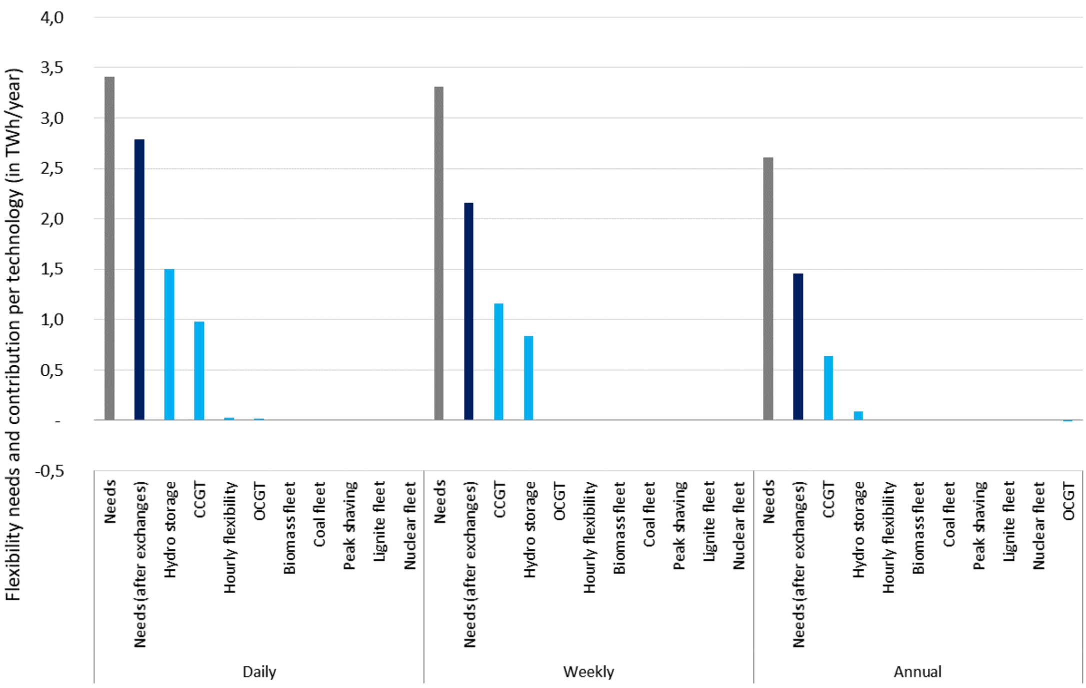

Figure 124: Contribution to flexibility needs per technology in Option (III)

The following graph shows the contribution of each technology to sub-hourly flexibility needs (i.e. participation in reserve procurement) in Option (III).

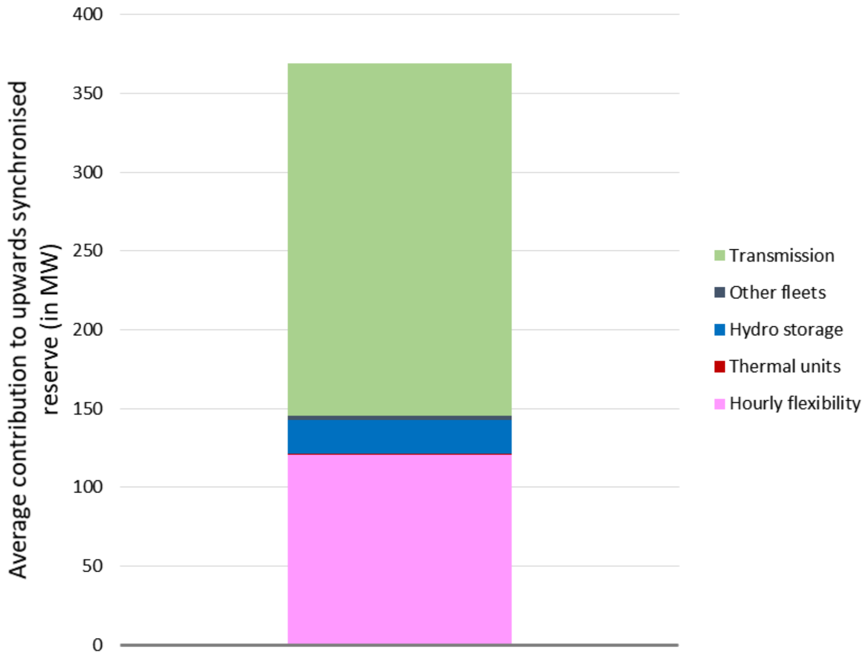

Figure 125: Contribution to upward synchronised reserve

Social welfare

The following table shows the evolution of the national social welfare between Option (II) and Option (I), and between Option (III) and Option (I), expressed in M€ per year.

The social welfare is defined as the sum of the producer surplus (driven by the difference between the market price and the variable generation cost), the consumer surplus (driven by the difference between what consumers would be ready to pay for electricity and the market price) and half the congestion rents (the revenues captured by interconnectors by exploiting the price difference between two zones).

The figures below do not take into account the savings in terms of investment costs, as these savings could be split between all the countries that have a common interest in a given project. At the EU28 level, compared to Option (I), these savings correspond to 150 M€ in Option (II) and to 210 M€ in Option (III).

	Evolution of social welfare (in M€ per year)
From Option (I) to Option (II)	+ 4 M€/y
From Option (I) to Option (III)	+ 13 M€/y

Table 78 - Evolution of social welfare

B.23 Romania

Scenario description and flexibility needs

The following tables provide information related to the assumptions inherited from the PRIMES EUCO30 scenario.

	EUCO30
Power demand (in TWh/y)	60.7
Variable RES generation (in TWh/y)	21.9
of which wind onshore	*17.8*
of which wind offshore	*0.0*
of which PV	*4.1*

Table 79 - Demand and variable RES generation

Baseload and mid-merit capacities	EUCO30
Nuclear (in GW)	2.83
Coal (in GW)	0.23
Lignite (in GW)	1.68

Table 80 - Baseload and mid-merit capacities

The following graph presents the trajectory of flexibility needs over the 2020-2030 period.

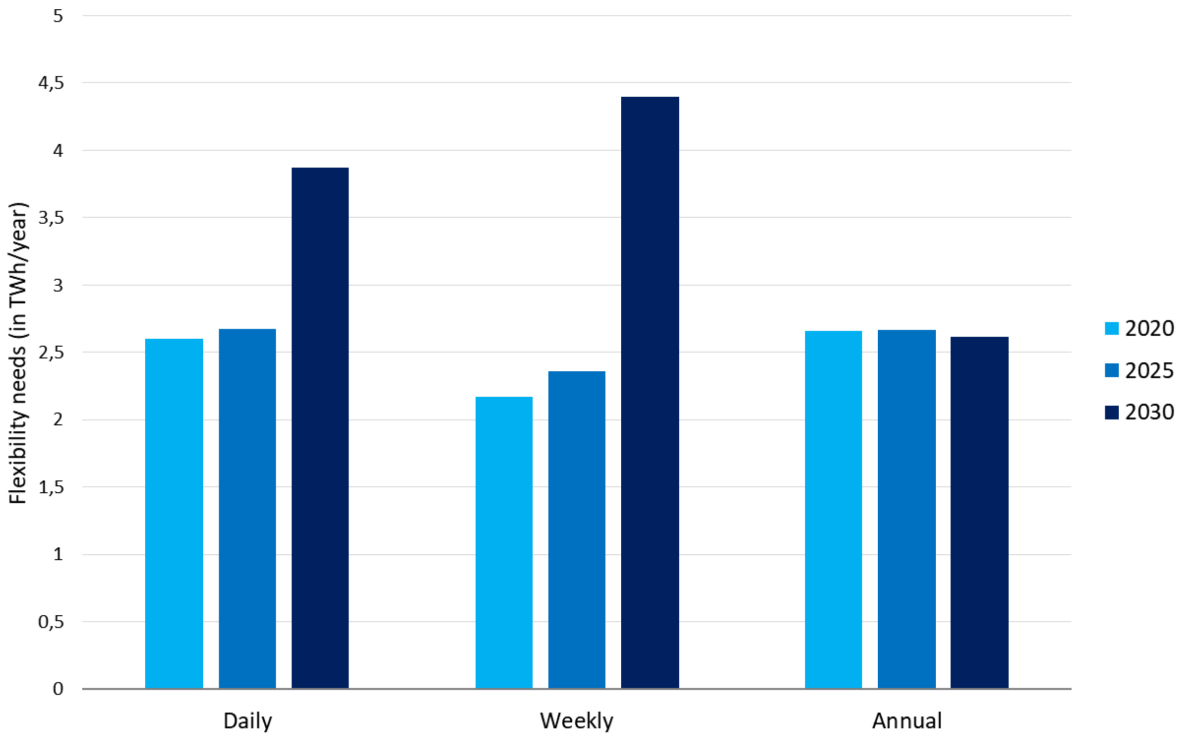

Figure 126 - Flexibility needs for 2020, 2025 and 2030

Flexibility portfolio

The following graph presents the potential for demand-response, storage and interconnectors, and the way these potentials are exploited in Options (II) and (III). Moreover, no batteries are found to be installed.

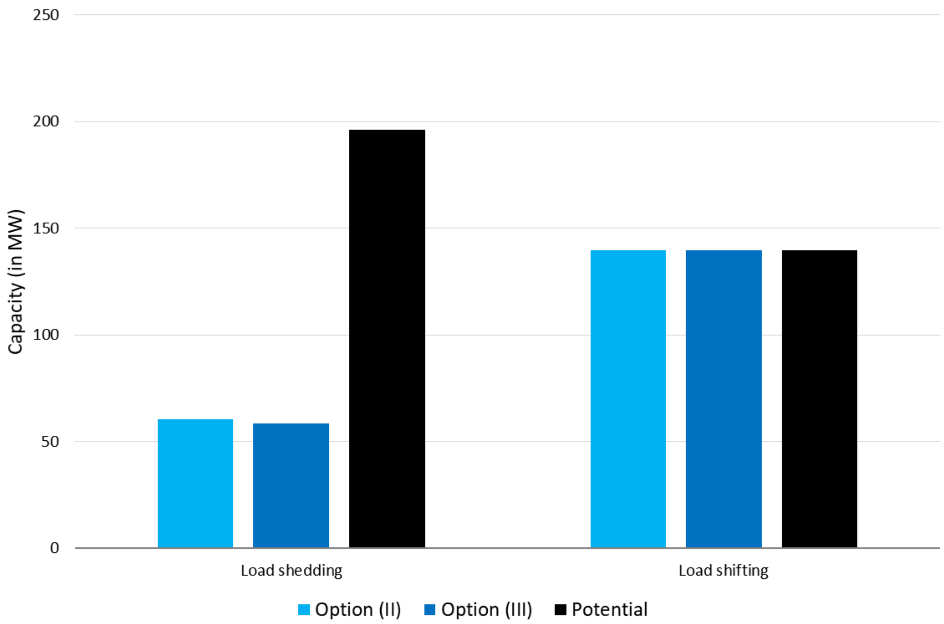

Figure 127 - Potential for flexibility solutions and installed capacities in Options (II) and (III)

Provision of flexibility

The following graph shows the contribution of each technology in the provision of daily, weekly and annual flexibility needs in Option (III).

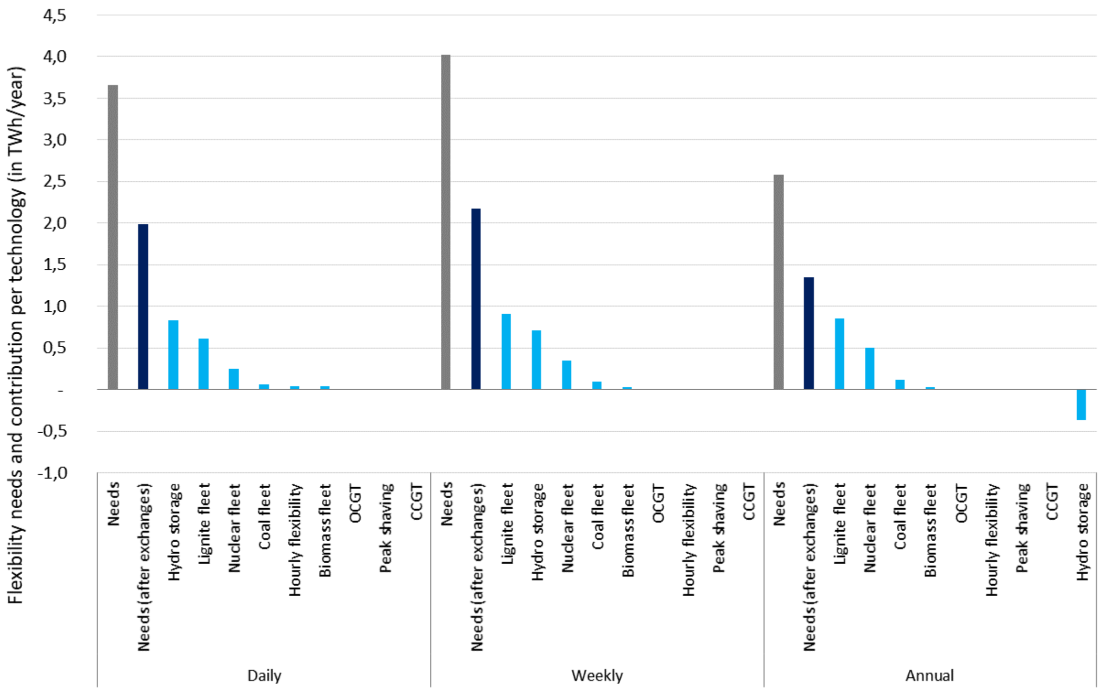

Figure 128: Contribution to flexibility needs per technology in Option (III)

The following graph shows the contribution of each technology to sub-hourly flexibility needs (i.e. participation in reserve procurement) in Option (III).

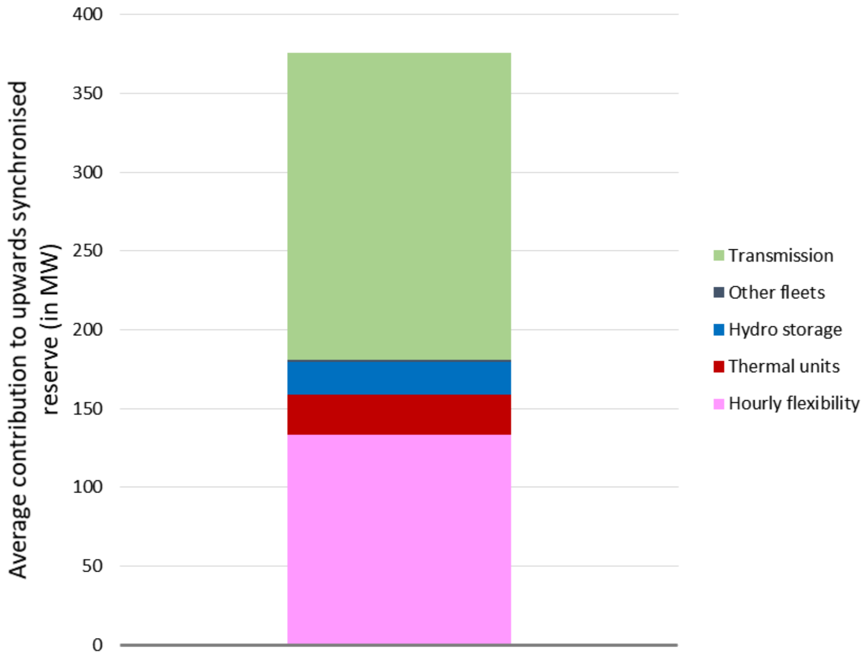

Figure 129: Contribution to upward synchronised reserve

Social welfare

The following table shows the evolution of the national social welfare between Option (II) and Option (I), and between Option (III) and Option (I), expressed in M€ per year.

The social welfare is defined as the sum of the producer surplus (driven by the difference between the market price and the variable generation cost), the consumer surplus (driven by the difference between what consumers would be ready to pay for electricity and the market price) and half the congestion rents (the revenues captured by interconnectors by exploiting the price difference between two zones).

The figures below do not take into account the savings in terms of investment costs, as these savings could be split between all the countries that have a common interest in a given project. At the EU28 level, compared to Option (I), these savings correspond to 150 M€ in Option (II) and to 210 M€ in Option (III).

	Evolution of social welfare (in M€ per year)
From Option (I) to Option (II)	+ 79 M€/y
From Option (I) to Option (III)	+ 85 M€/y

Table 81 - Evolution of social welfare

B.24 Slovakia

Scenario description and flexibility needs

The following tables provide information related to the assumptions inherited from the PRIMES EUCO30 scenario.

	EUCO30
Power demand (in TWh/y)	32.8
Variable RES generation (in TWh/y)	1.0
of which wind onshore	*0.4*
of which wind offshore	*0.0*
of which PV	*0.6*

Table 82 - Demand and variable RES generation

Baseload and mid-merit capacities	EUCO30
Nuclear (in GW)	4.02
Coal (in GW)	0.33
Lignite (in GW)	0.13

Table 83 - Baseload and mid-merit capacities

The following graph presents the trajectory of flexibility needs over the 2020-2030 period.

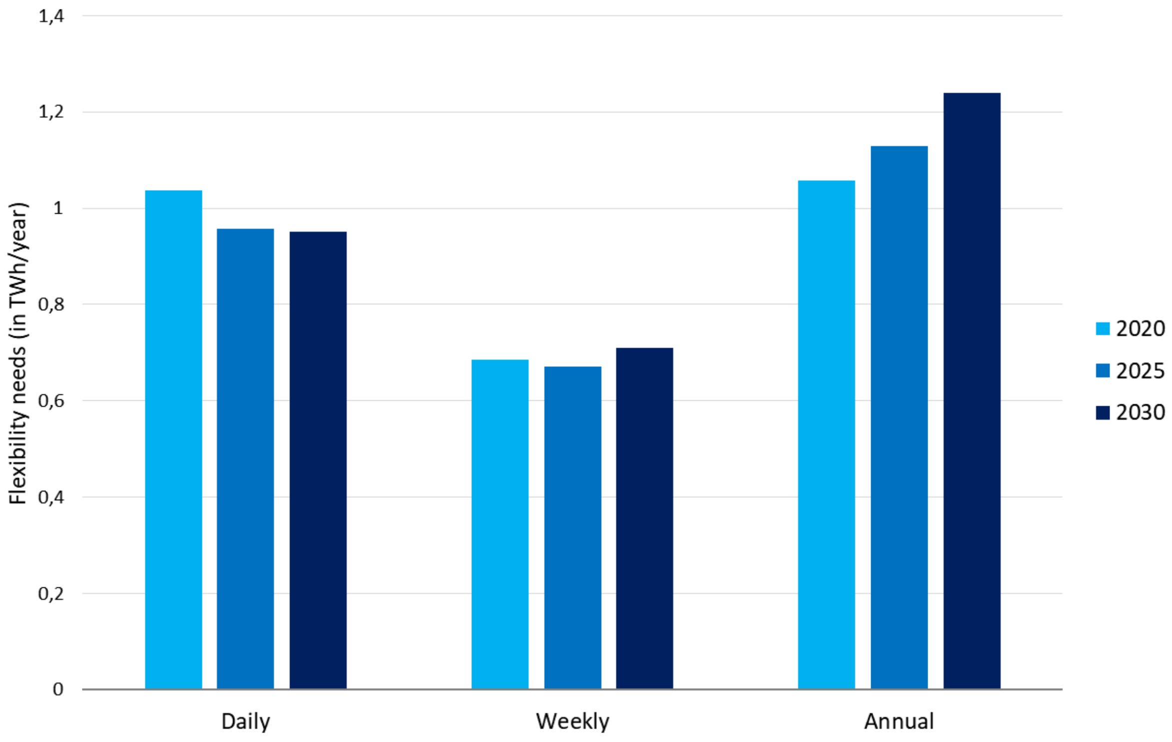

Figure 130 - Flexibility needs for 2020, 2025 and 2030

Flexibility portfolio

The following graph presents the potential for demand-response, storage and interconnectors, and the way these potentials are exploited in Options (II) and (III). Moreover, 30 MW of batteries are found to be installed in Options (II) and (III).

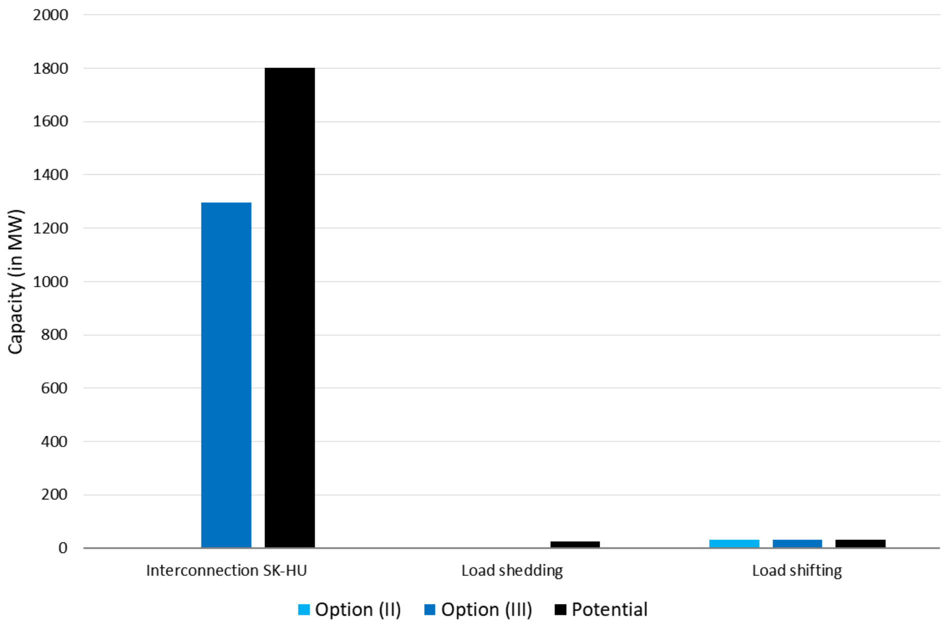

Figure 131 - Potential for flexibility solutions and installed capacities in Options (II) and (III)

Provision of flexibility

The following graph shows the contribution of each technology in the provision of daily, weekly and annual flexibility needs in Option (III).

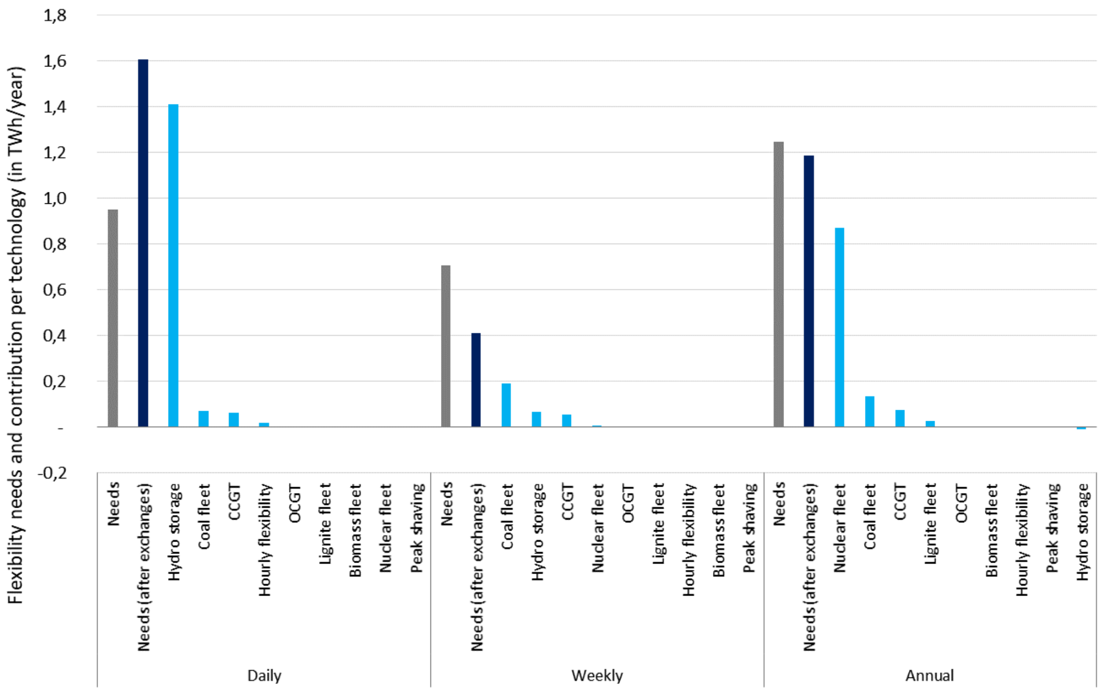

Figure 132: Contribution to flexibility needs per technology in Option (III)

The following graph shows the contribution of each technology to sub-hourly flexibility needs (i.e. participation in reserve procurement) in Option (III).

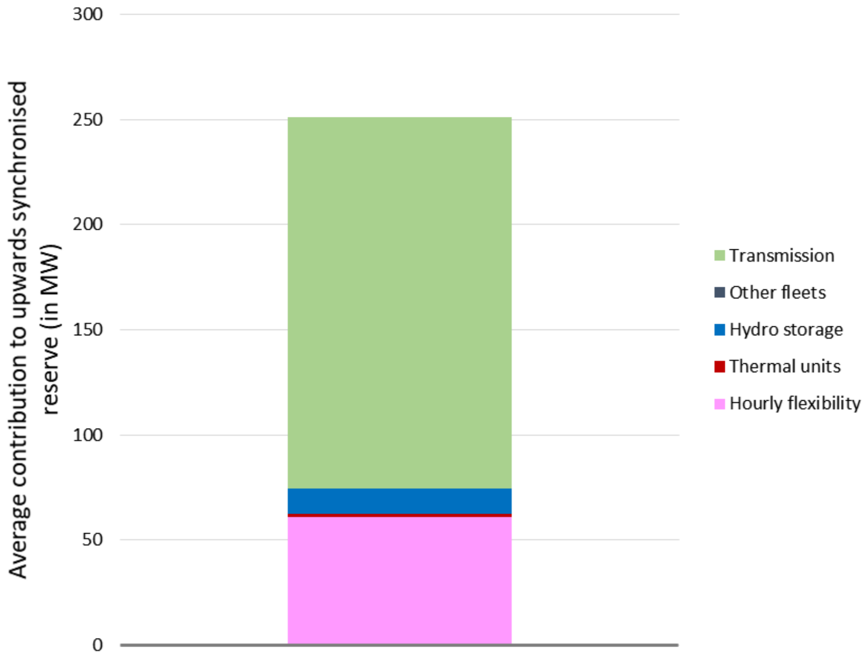

Figure 133: Contribution to upward synchronised reserve

Social welfare

The following table shows the evolution of the national social welfare between Option (II) and Option (I), and between Option (III) and Option (I), expressed in M€ per year.

The social welfare is defined as the sum of the producer surplus (driven by the difference between the market price and the variable generation cost), the consumer surplus (driven by the difference between what consumers would be ready to pay for electricity and the market price) and half the congestion rents (the revenues captured by interconnectors by exploiting the price difference between two zones).

The figures below do not take into account the savings in terms of investment costs, as these savings could be split between all the countries that have a common interest in a given project. At the EU28 level, compared to Option (I), these savings correspond to 150 M€ in Option (II) and to 210 M€ in Option (III).

	Evolution of social welfare (in M€ per year)
From Option (I) to Option (II)	- 6 M€/y
From Option (I) to Option (III)	- 5 M€/y

Table 84 - Evolution of social welfare

B.25 Slovenia

Scenario description and flexibility needs

The following tables provide information related to the assumptions inherited from the PRIMES EUCO30 scenario.

	EUCO30
Power demand (in TWh/y)	15.6
Variable RES generation (in TWh/y)	2.4
of which wind onshore	*0.5*
of which wind offshore	*0.0*
of which PV	*1.9*

Table 85 - Demand and variable RES generation

Baseload and mid-merit capacities	EUCO30
Nuclear (in GW)	0.70
Coal (in GW)	0.07
Lignite (in GW)	0.56

Table 86 - Baseload and mid-merit capacities

The following graph presents the trajectory of flexibility needs over the 2020-2030 period.

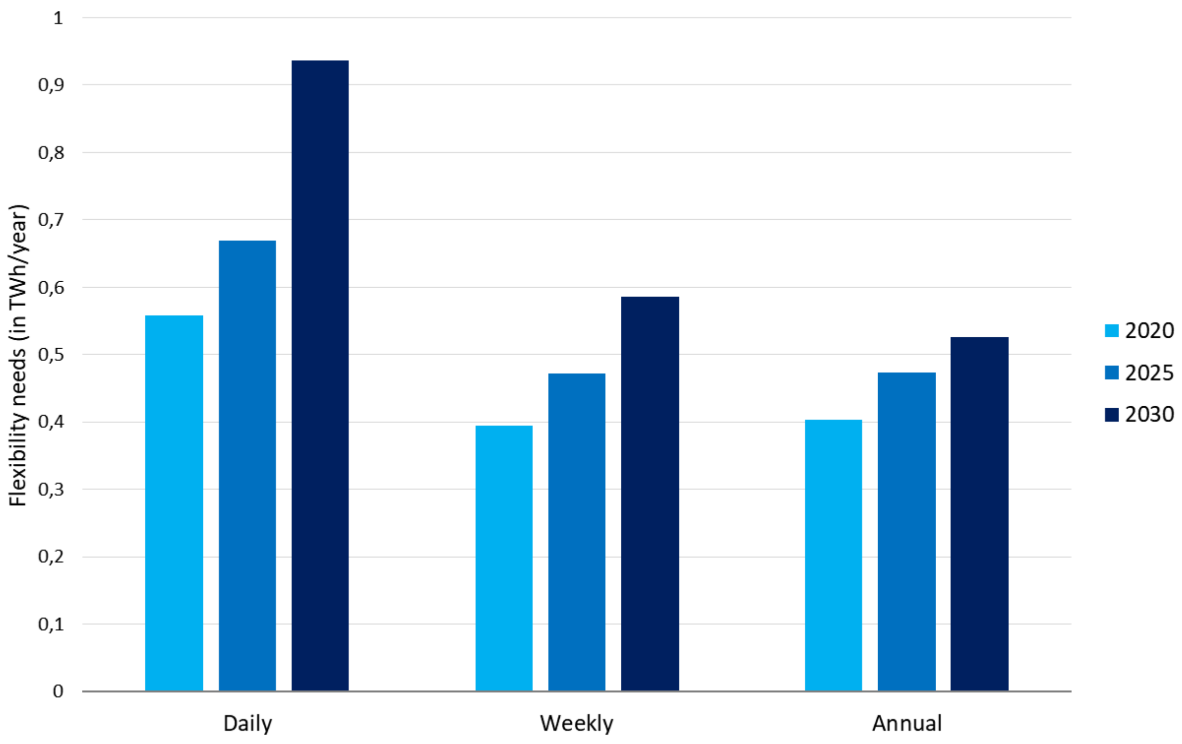

Figure 134 - Flexibility needs for 2020, 2025 and 2030

Flexibility portfolio

The following graph presents the potential for demand-response, storage and interconnectors, and the way these potentials are exploited in Options (II) and (III). Moreover, 10 MW of batteries are found to be installed in Options (II) and (III).

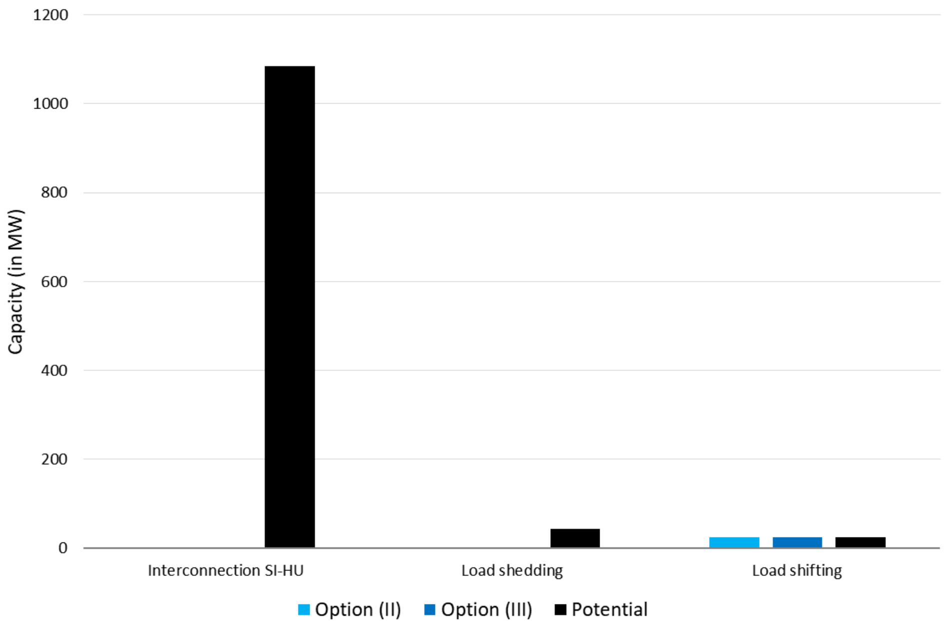

Figure 135 - Potential for flexibility solutions and installed capacities in Options (II) and (III)

Provision of flexibility

The following graph shows the contribution of each technology in the provision of daily, weekly and annual flexibility needs in Option (III).

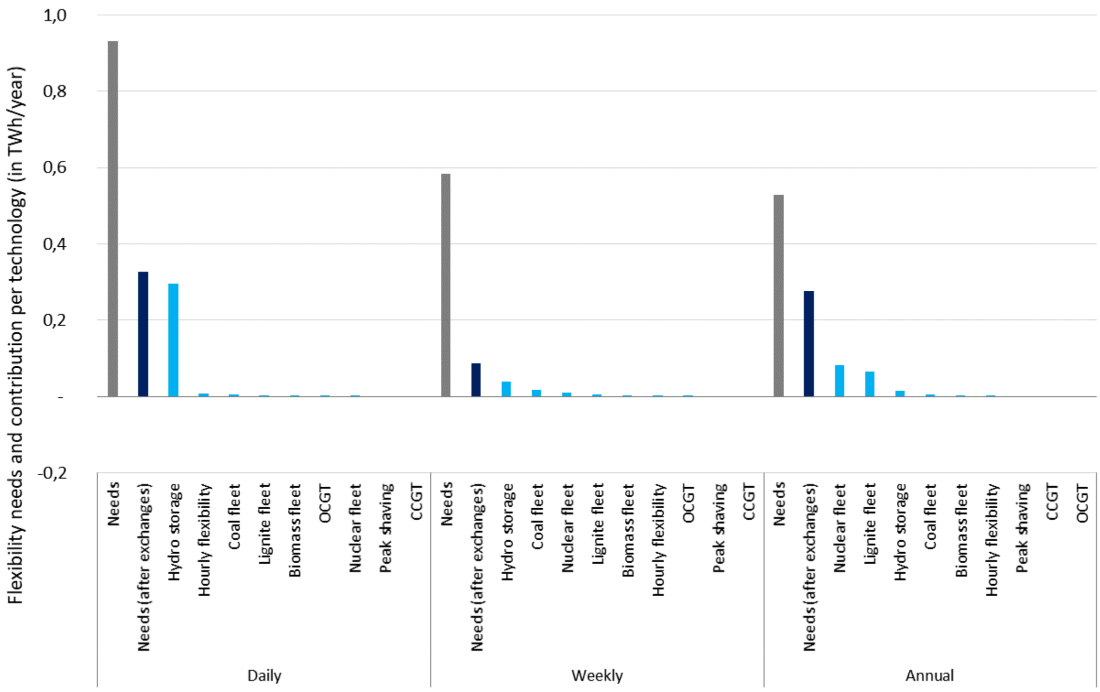

Figure 136: Contribution to flexibility needs per technology in Option (III)

The following graph shows the contribution of each technology to sub-hourly flexibility needs (i.e. participation in reserve procurement) in Option (III).

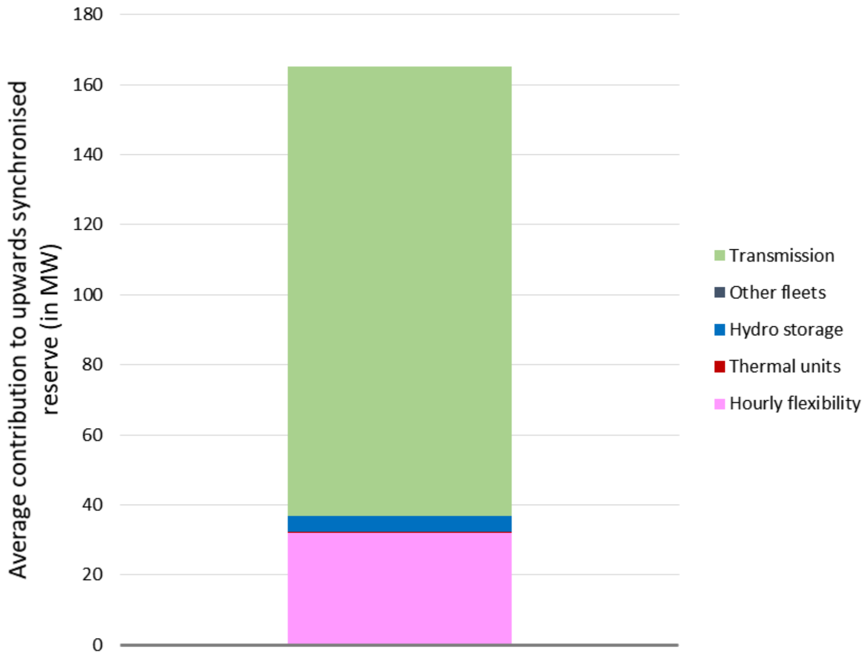

Figure 137: Contribution to upward synchronised reserve

Social welfare

The following table shows the evolution of the national social welfare between Option (II) and Option (I), and between Option (III) and Option (I), expressed in M€ per year.

The social welfare is defined as the sum of the producer surplus (driven by the difference between the market price and the variable generation cost), the consumer surplus (driven by the difference between what consumers would be ready to pay for electricity and the market price) and half the congestion rents (the revenues captured by interconnectors by exploiting the price difference between two zones).

The figures below do not take into account the savings in terms of investment costs, as these savings could be split between all the countries that have a common interest in a given project. At the EU28 level, compared to Option (I), these savings correspond to 150 M€ in Option (II) and to 210 M€ in Option (III).

	Evolution of social welfare (in M€ per year)
From Option (I) to Option (II)	+ 4 M€/y
From Option (I) to Option (III)	+ 4 M€/y

Table 87 - Evolution of social welfare

B.26 Spain

Scenario description and flexibility needs

The following tables provide information related to the assumptions inherited from the PRIMES EUCO30 scenario.

	EUCO30
Power demand (in TWh/y)	274.6
Variable RES generation (in TWh/y)	145.8
of which wind onshore	*84.7*
of which wind offshore	*0.2*
of which PV	*60.9*

Table 88 - Demand and variable RES generation

Baseload and mid-merit capacities	EUCO30
Nuclear (in GW)	7.40
Coal (in GW)	3.97
Lignite (in GW)	0.00

Table 89 - Baseload and mid-merit capacities

The following graph presents the trajectory of flexibility needs over the 2020-2030 period.

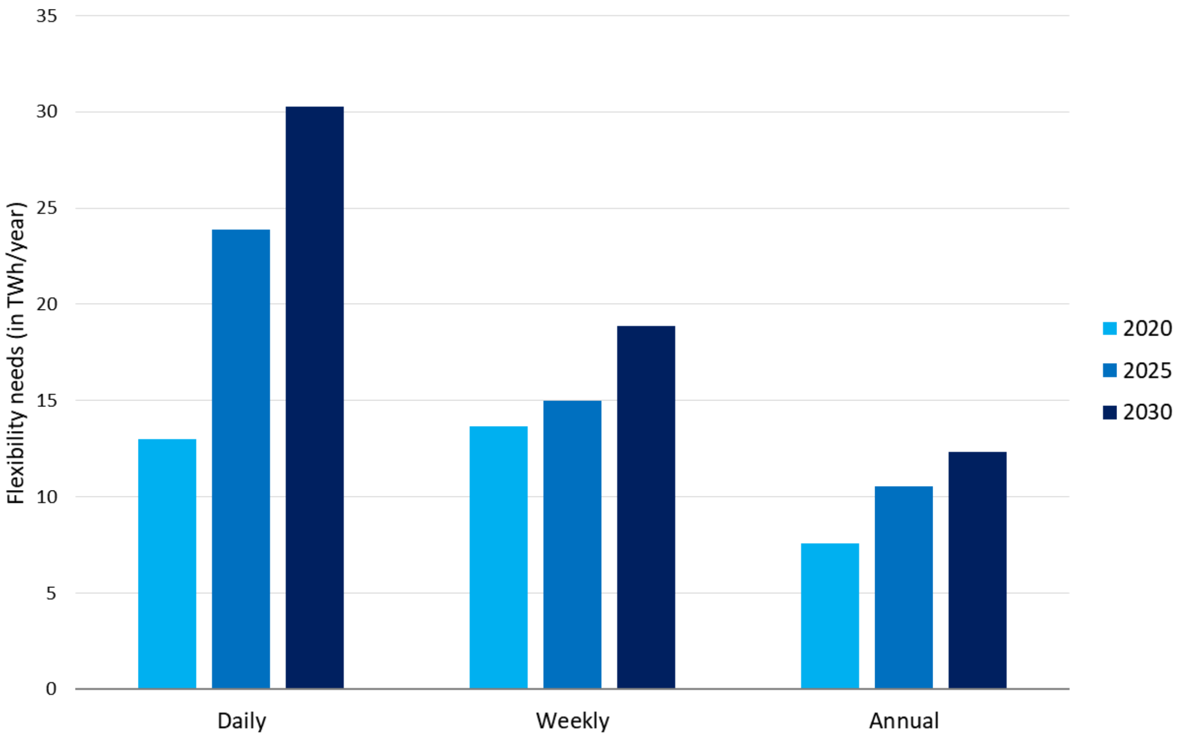

Figure 138 - Flexibility needs for 2020, 2025 and 2030

Flexibility portfolio

The following graph presents the potential for demand-response, storage and interconnectors, and the way these potentials are exploited in Options (II) and (III). Moreover, no batteries are found to be installed.

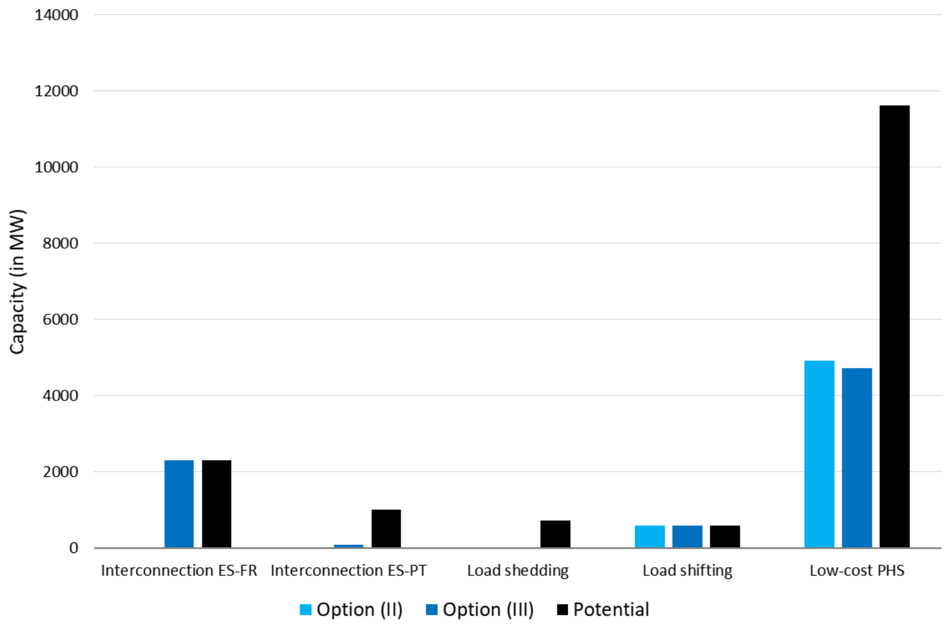

Figure 139: Potential for flexibility solutions and installed capacities in Options (II) and (III)

Provision of flexibility

The following graph shows the contribution of each technology in the provision of daily, weekly and annual flexibility needs in Option (III).

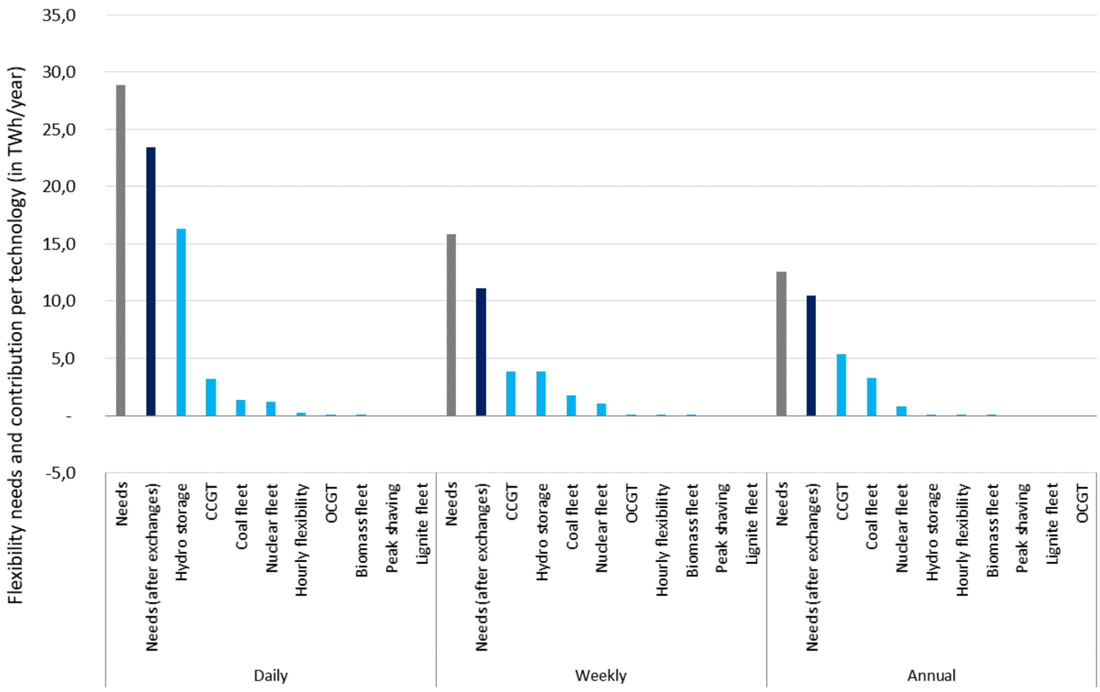

Figure 140: Contribution to flexibility needs per technology in Option (III)

The following graph shows the contribution of each technology to sub-hourly flexibility needs (i.e. participation in reserve procurement) in Option (III).

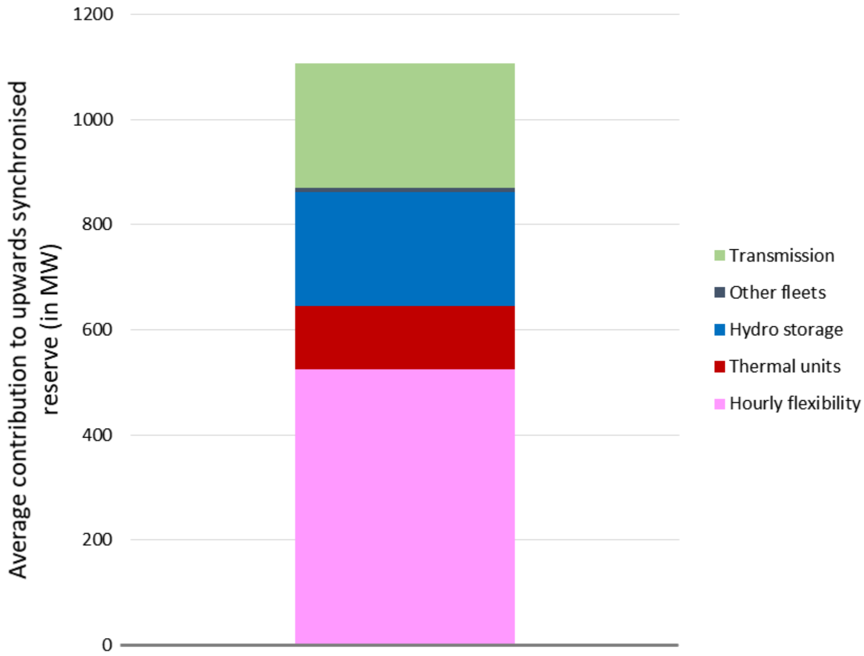

Figure 141: Contribution to upward synchronised reserve

Social welfare

The following table shows the evolution of the national social welfare between Option (II) and Option (I), and between Option (III) and Option (I), expressed in M€ per year.

The social welfare is defined as the sum of the producer surplus (driven by the difference between the market price and the variable generation cost), the consumer surplus (driven by the difference between what consumers would be ready to pay for electricity and the market price) and half the congestion rents (the revenues captured by interconnectors by exploiting the price difference between two zones).

The figures below do not take into account the savings in terms of investment costs, as these savings could be split between all the countries that have a common interest in a given project. At the EU28 level, compared to Option (I), these savings correspond to 150 M€ in Option (II) and to 210 M€ in Option (III).

	Evolution of social welfare (in M€ per year)
From Option (I) to Option (II)	+ 640 M€/y
From Option (I) to Option (III)	+ 760 M€/y

Table 90 - Evolution of social welfare

B.27 Sweden

Scenario description and flexibility needs

The following tables provide information related to the assumptions inherited from the PRIMES EUCO30 scenario.

	EUCO30
Power demand (in TWh/y)	159.4
Variable RES generation (in TWh/y)	37.8
of which wind onshore	*37.1*
of which wind offshore	*0.7*
of which PV	*0.1*

Table 91 - Demand and variable RES generation

Baseload and mid-merit capacities	EUCO30
Nuclear (in GW)	6.95
Coal (in GW)	0.10
Lignite (in GW)	0.02

Table 92 - Baseload and mid-merit capacities

The following graph presents the trajectory of flexibility needs over the 2020-2030 period.

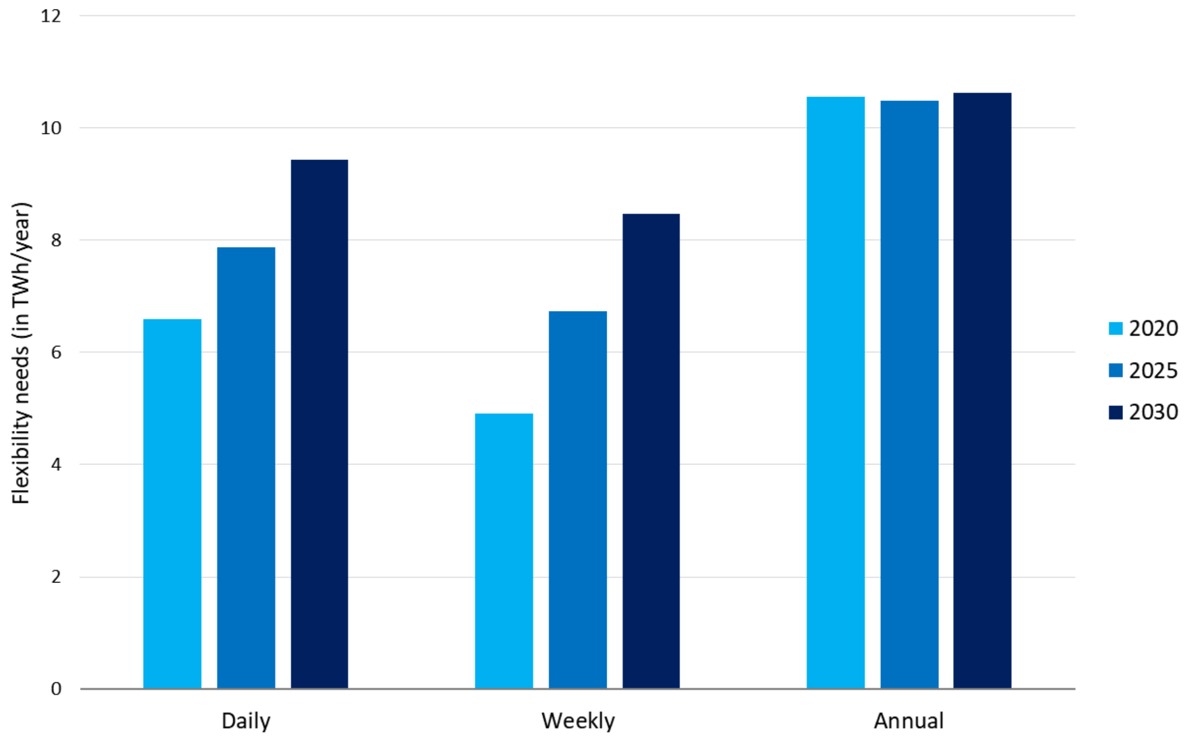

Figure 142 - Flexibility needs for 2020, 2025 and 2030

Flexibility portfolio

The following graph presents the potential for demand-response, storage and interconnectors, and the way these potentials are exploited in Options (II) and (III). Moreover, around 450 MW of batteries are found to be installed in Options (II) and (III).

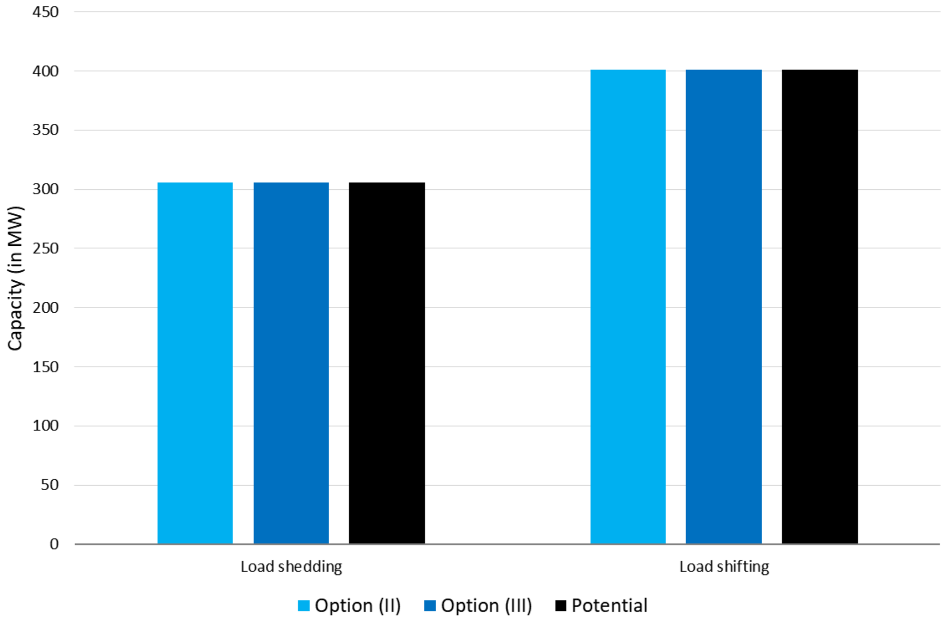

Figure 143 - Potential for flexibility solutions and installed capacities in Options (II) and (III)

Provision of flexibility

The following graph shows the contribution of each technology in the provision of daily, weekly and annual flexibility needs in Option (III).

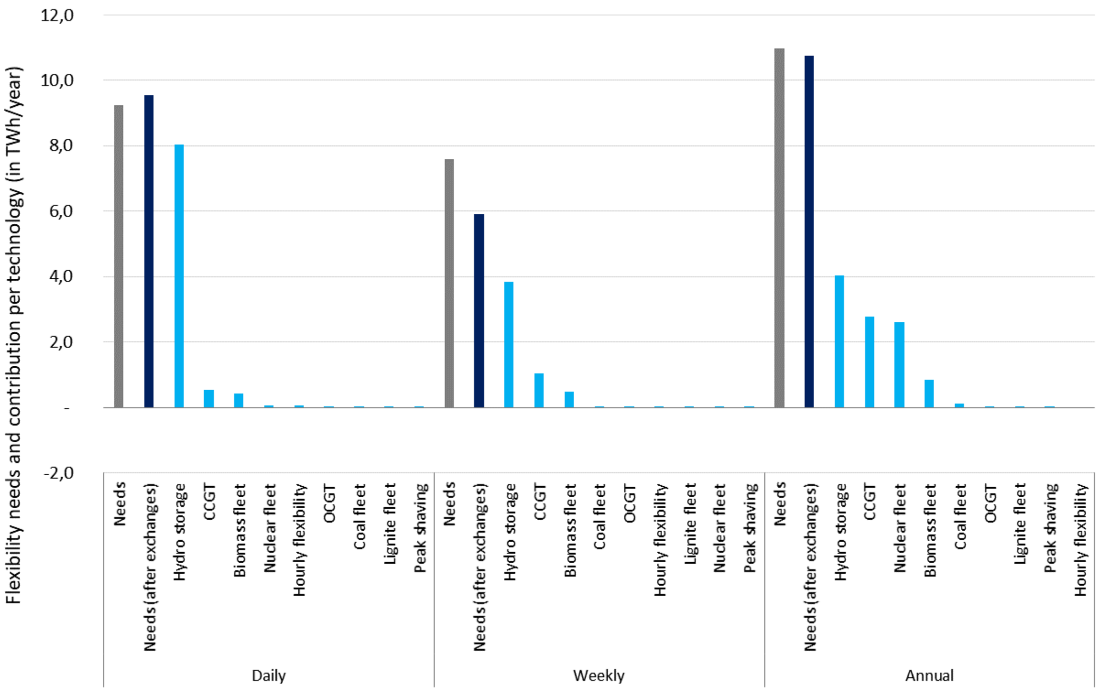

Figure 144: Contribution to flexibility needs per technology in Option (III)

The following graph shows the contribution of each technology to sub-hourly flexibility needs (i.e. participation in reserve procurement) in Option (III).

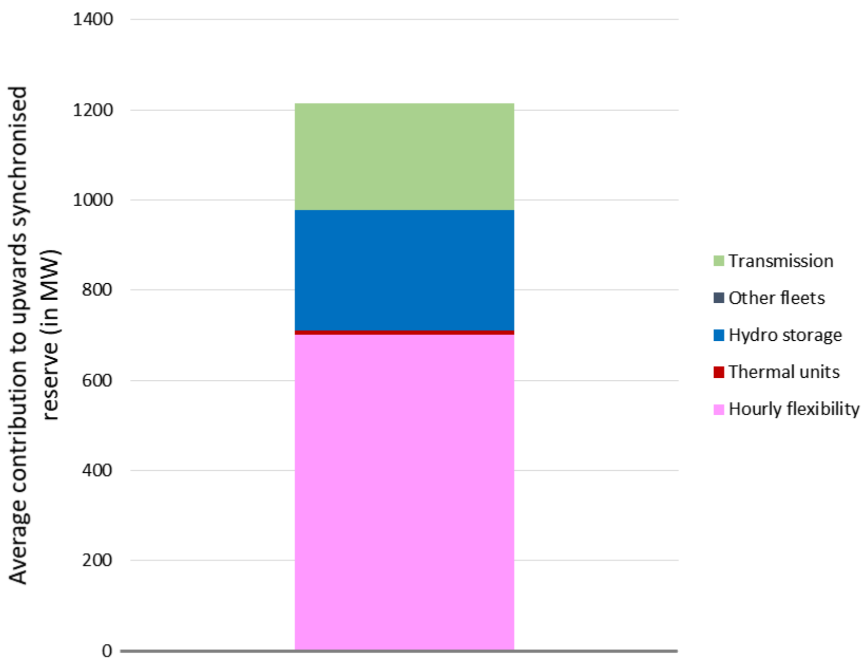

Figure 145: Contribution to upward synchronised reserve

Social welfare

The following table shows the evolution of the national social welfare between Option (II) and Option (I), and between Option (III) and Option (I), expressed in M€ per year.

The social welfare is defined as the sum of the producer surplus (driven by the difference between the market price and the variable generation cost), the consumer surplus (driven by the difference between what consumers would be ready to pay for electricity and the market price) and half the congestion rents (the revenues captured by interconnectors by exploiting the price difference between two zones).

The figures below do not take into account the savings in terms of investment costs, as these savings could be split between all the countries that have a common interest in a given project. At the EU28 level, compared to Option (I), these savings correspond to 150 M€ in Option (II) and to 210 M€ in Option (III).

	Evolution of social welfare (in M€ per year)
From Option (I) to Option (II)	+ 83 M€/y
From Option (I) to Option (III)	+ 75 M€/y

Table 93 - Evolution of social welfare

B.28 United Kingdom

Scenario description and flexibility needs

The following tables provide information related to the assumptions inherited from the PRIMES EUCO30 scenario.

	EUCO30
Power demand (in TWh/y)	385.1
Variable RES generation (in TWh/y)	125.1
of which wind onshore	*73.2*
of which wind offshore	*42.9*
of which PV	*9.0*

Table 94 - Demand and variable RES generation

Baseload and mid-merit capacities	EUCO30
Nuclear (in GW)	13.11
Coal (in GW)	0.50
Lignite (in GW)	0.00

Table 95 - Baseload and mid-merit capacities

The following graph presents the trajectory of flexibility needs over the 2020-2030 period.

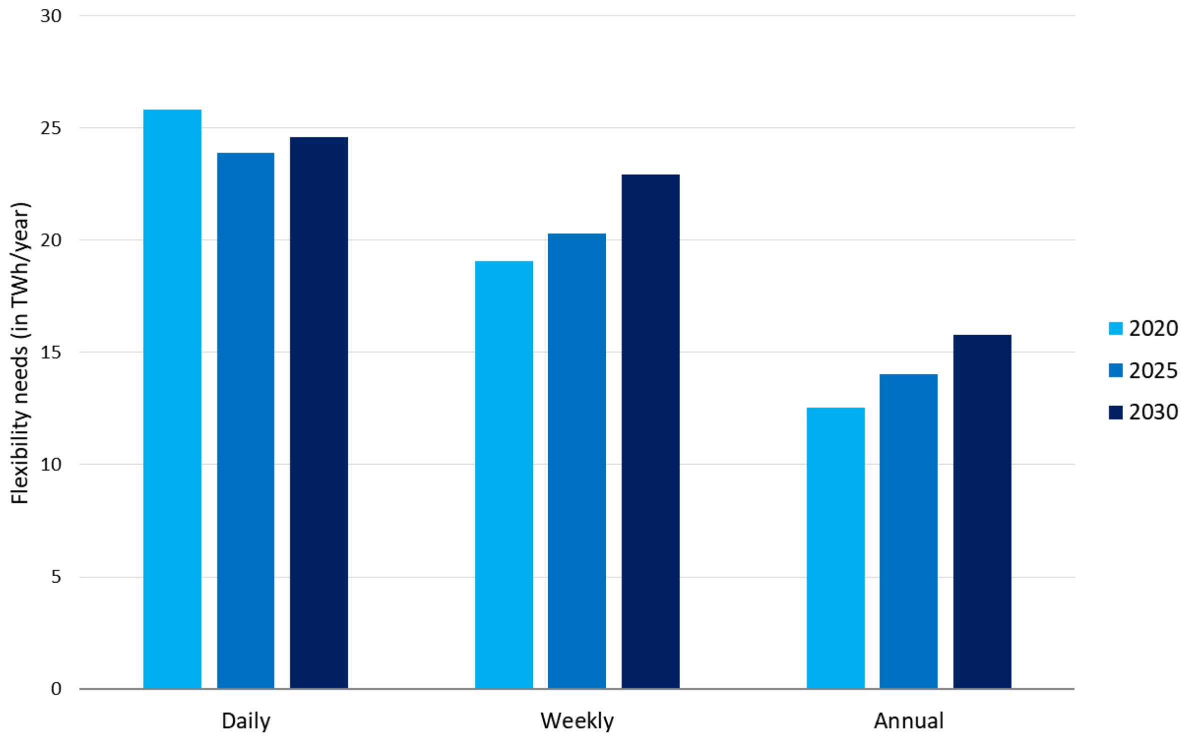

Figure 146 - Flexibility needs for 2020, 2025 and 2030

Flexibility portfolio

The following graph presents the potential for demand-response, storage and interconnectors, and the way these potentials are exploited in Options (II) and (III). Moreover, around 400 MW of batteries are found to be installed in Options (II) and (III).

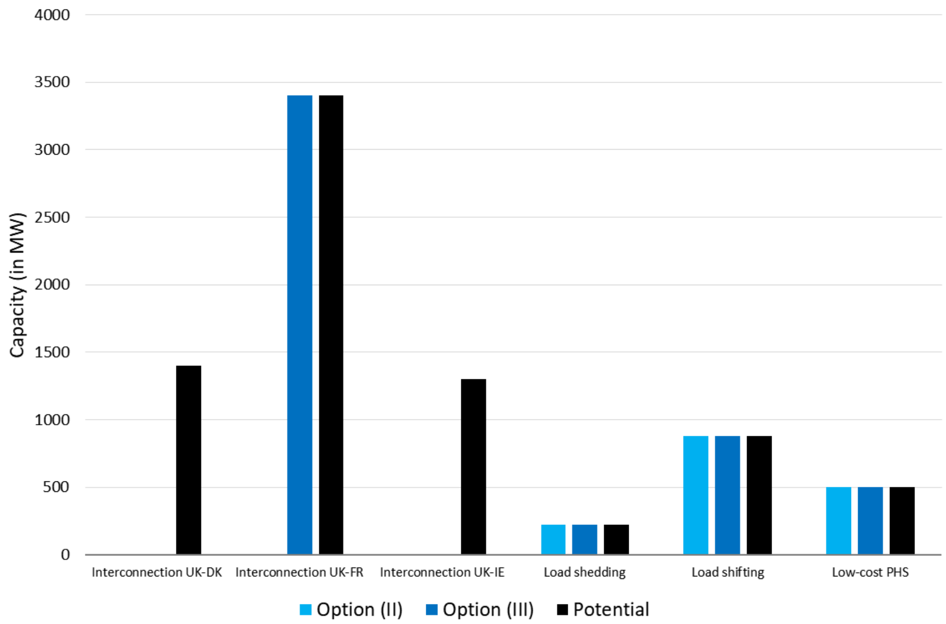

Figure 147 - Potential for flexibility solutions and installed capacities in Options (II) and (III)

Provision of flexibility

The following graph shows the contribution of each technology in the provision of daily, weekly and annual flexibility needs in Option (III).

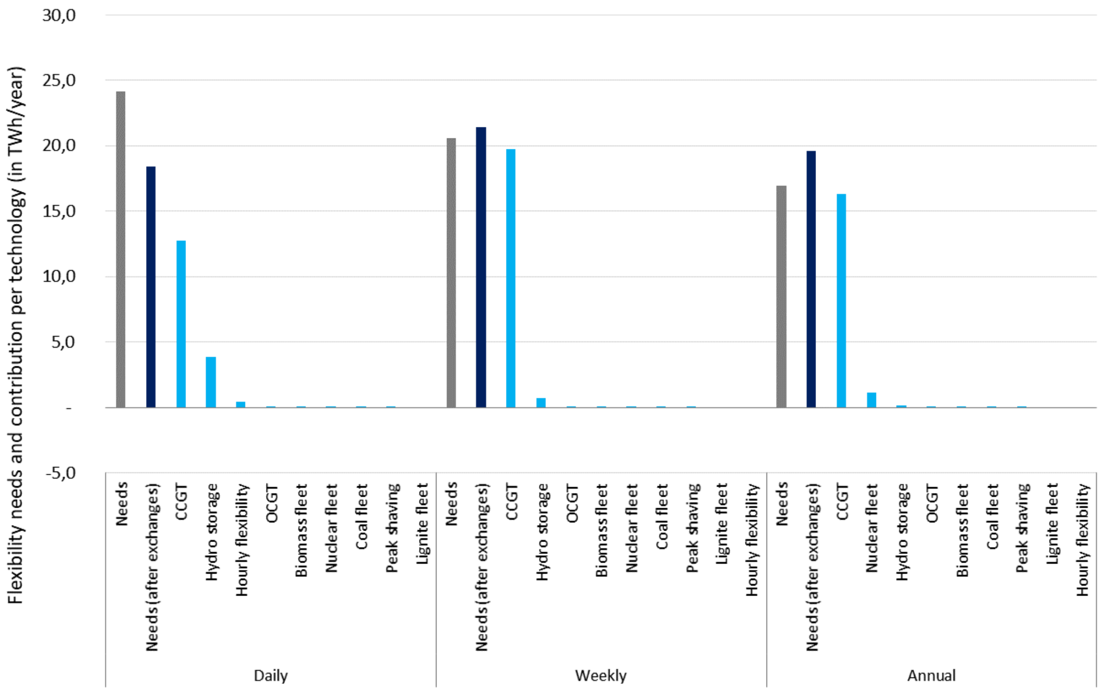

Figure 148: Contribution to flexibility needs per technology in Option (III)

The following graph shows the contribution of each technology to sub-hourly flexibility needs (i.e. participation in reserve procurement) in Option (III).

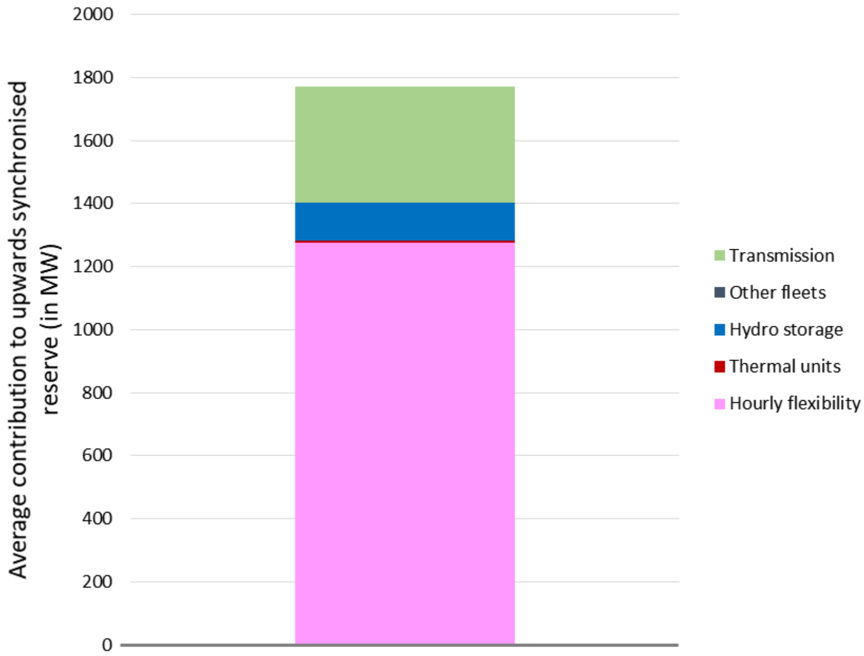

Figure 149: Contribution to upward synchronised reserve

Social welfare

The following table shows the evolution of the national social welfare between Option (II) and Option (I), and between Option (III) and Option (I), expressed in M€ per year.

The social welfare is defined as the sum of the producer surplus (driven by the difference between the market price and the variable generation cost), the consumer surplus (driven by the difference between what consumers would be ready to pay for electricity and the market price) and half the congestion rents (the revenues captured by interconnectors by exploiting the price difference between two zones).

The figures below do not take into account the savings in terms of investment costs, as these savings could be split between all the countries that have a common interest in a given project. At the EU28 level, compared to Option (I), these savings correspond to 150 M€ in Option (II) and to 210 M€ in Option (III).

	Evolution of social welfare (in M€ per year)
From Option (I) to Option (II)	+ 190 M€/y
From Option (I) to Option (III)	+ 260 M€/y

Table 96 - Evolution of social welfare