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Integrating solar plants into the European power grid – What is the optimal capacity combination of PV and battery storage?

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ABSTRACT

The European Union's FIT-for-55 and RePower EU policies set forth highly ambitious targets for the deployment of variable renewables. As a result, there will be a significant increase in PV capacity in the short term up to 2030, which will require greater power system flexibility. One effective solution is the use of battery storage. Given the exponential growth in PV generation over the past years and its expected continued growth, this article examines the optimal level of battery storage required to balance this growth in a cost-efficient way. The Total System Cost indicator is used to measure efficiency in the power sector, including both investment and generation costs in the European power system. The assessment demonstrates that there is a cost-optimal capacity combination of PV and battery storage at the European level. Compared to the EU's 2030 target of 383–592 GW of solar capacity, our results show that in a range of 530–880 GW of PV combined with battery storage equivalent to 2.5–7.5% of the total intermittent capacity represents the cost optimal range in the system. The results suggest, that moving toward higher deployment of PV (above 880 GW), the total cost of the system increases sharply even with applying higher level of battery storage. The results also suggest that targeting lower PV deployment ambition is not cost optimal either. Our findings indicate that batteries can play a significant role in reducing the curtailment of solar energy and can also mitigate the strong cannibalisation effect of PV installations.

1. Introduction

Climate change represents the most significant risk to the environment and society in recent decades, with accelerating impacts. Despite the Paris Agreement and numerous pledges, the continued increase in atmospheric carbon dioxide concentration necessitates rapid changes. Europe is at the forefront of decarbonisation efforts, with already achieved results and ambitious goals for the coming decades, particularly in the power sector.

However, the greening of the European electricity system also requires increasing flexibility [1]. Battery energy storage systems (BESS) represent a crucial component of the solution. In a similar manner to most novel and pioneering technologies, the installation of battery storage receives financial support in many EU countries (see Table 1) presently, due to its higher investment cost level. To ensure a sufficient supply of flexible sources within the system, numerous countries have implemented BESS support schemes in recent years or have at least established targets for battery storage capacities (see Table 1 for references).

However, there is currently no harmonised approach throughout Europe with regard to battery installation. The extent to which renewable energy sources necessitate the integration of battery storage remains uncertain, as does the optimal level of battery storage capacity required to provide the requisite flexibility. The answers to these questions depend on several factors and attributes of the electricity systems in question. One of the most significant drivers is the large-scale deployment of solar plants. However, other characteristics, such as the availability of inexpensive and reliable flexibility sources (e.g. regulable hydro) or the interconnection capacities, are also important factors. This paper presents a novel approach to the harmonisation of PV and battery storage capacity planning. It contributes to the literature by two new aspects. It presents a cost-minimising PV and battery storage deployment pathway on a European level by applying a much wider range of possible capacity pathways for both technologies. It goes beyond the EU FIT for 55 and RePower EU targets in PV deployment, as recent growth trends and studies show a much higher window of opportunity in the solar technology, if combined with battery storage [2,3]. Second, the applied model optimises the total system cost in the power sector, including not only variable and fixed annualised investments costs, but also the costs of the ancillary services markets, generally overlooked in most power system models.

The subsequent section presents a summary of the results and approaches of similar previous studies, thereby underlying the elements of our research that address the remaining gaps in the literature. The third

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section outlines the modelling methodology and scenario setup. The fourth section describes the main findings, while the final section contains the conclusions and the possible future steps in the research.

2. Literature review

2.1. Battery storage and variable renewable capacity targets in the EU power sector

The approaches to battery storage capacity planning pursued by member states vary considerably. While the deployment of photovoltaic plants represents the most significant driver of flexibility needs, as evidenced by the latest National Energy and Climate Plans (NECPs) and available information on active policies and measures, there is no evident correlation between planned PV capacity and BESS capacity developments in European Member States.

In Hungary, the rapid uptake of PV capacities, which is expected to reach approximately 7 GW in 2025 and 12 GW in 2030, is accompanied by a planned 500–600 MW BESS by 2026 and 1 GW by 2030. In Spain, the planned online capacity of PV is estimated to be ~ 57 GW by 2025 and ~ 76 GW by 2030, with 9 and 18.5 GW of storage capacity, respectively. In Lithuania, 200 MW of BESS capacity has already been added, while the planned penetration of PV is expected to exceed 4 GW in 2025 and 5 GW by 2030.

It is evident that the majority of countries with the highest targeted PV capacity (in comparison to their overall electricity consumption) have either already supported or are currently supporting BESS projects in some form. Table 1 provides a summary of the planned future variable renewable energy sources (vRES) and BESS capacities in all EU countries with references, where either BESS targets are set in the NECP or a BESS support scheme is in place or is about to be launched (as of December 2023).

Table 1 illustrates that there is yet no consensus among MSs on the optimal methodology for installing battery storage systems to efficiently address the flexibility needs induced by vRES capacities, particularly those associated with PV plants.

2.2. Former research on the optimal share of BESS

A considerable number of studies have analysed the role of energy storage in power systems characterised by a high share of vRES. The challenge lies in the uncertainty surrounding both the anticipated proportion of vRES over the next 25 years and the technologies that will be employed to provide flexibility, such as BESS based on Li-Ion, flow batteries, pump hydro, or other innovative technologies like Compressed Air Energy Storage (CAES) [17]. Furthermore, technologies such as concentrating solar with heat storage may play a similar role (for example, a similar project was already supported in Estonia [5]). The transmission system represents an additional dimension that is crucial to the future development of the energy system and the determination of the optimal share of BESS. Child et al. [2] concluded that the energy system model assessment demonstrated that 100 % renewable energy is achievable in a cost-optimal manner if there is a significant increase in net transfer capacities between regions, with a focus on various renewable energy sources (such as offshore wind or photovoltaic), and further expansion of storage technologies.

Several studies have highlighted the importance of the relative shares of photovoltaic (PV) and wind technologies (e.g. [18,19]). A system with a high PV capacity may necessitate substantial short-term storage, such as battery energy storage systems (BESS), whereas a system with a higher wind capacity may require long-term storage or robust transmission networks. In their 2016 study, Bretsch et al. [20] employed a linear investment and dispatch optimisation model for the EU, emphasising the role of BESS in minimising curtailments of vRES and enhancing the availability of flexible generation in the future, given the significantly higher volatility in residual load.

It is crucial to determine the objective of the assessment precisely. To ascertain the optimal power system model capable of drawing valid

Table 1
Planned PV, wind and battery storage capacities, and BESS support schemes.

	PV capacity (2030)	Wind capacity (2030)	BESS capacity (2030)	Battery/ total VRES	Battery/ PV	BESS Support scheme	Source
Belgium	19.1 GW	5.5 GW	2.7 GW	10.98 %	14.14 %	n.a.	[4,5]
Bulgaria	6.8 GW	2.5 GW	1.28 GW	13.76 %	18.82 %	Yes, financed from RRF	[5]
Czech Republic	10.1 GW	1.5 GW	1.74 GW	15.00 %	17.23 %	Yes, direct support	[5]
Cyprus	0.9 GW	0.2 GW	50 MW	4.70 %	5.60 %	Yes, being prepared, for RES + BESS systems	[4,5]
Germany	215 GW	145 GW	no target, existing battery capacity is 8.5 GW	2.40 %	4.00 %	Former support scheme for PV + BESS	[4,6]
Estonia	1.2 GW	2.3 GW	No information on overall capacity	n.a.	0 %	Yes, financed from RRF	[4,5,7]
Spain	76 GW	62 GW	Overall storage capacity: 22 GW	13.40 %	24.20 %	Yes	[4,5,8]
Finland	5.8 GW	10 GW	1 GW	6.33 %	17.24 %	n.a.	[5]
France	54 GW	36.6 GW	3.3 GW (forecast)	3.64 %	6.11 %	n.a.	[5,9]
Greece	13.4 GW	10 GW	3.1 GW (+ pumped storage 2.2 GW)	13.50 %	23.80 %	Yes, financed from RRF	[4,5,8,10,11 17]
Hungary	12 GW	1 GW	1 GW	7.60 %	8.30 %	Yes, financed from RRF	[4,5,12]
Ireland	8 GW	14 GW	2 to 3.9 GW (forecast)	17.73 %	48.75 %	n.a.	[5,9 13]
Italy	77.9 GW	28.1 GW	7.9 GW	7.30 %	9.90 %	Yes (to be launched in 2024)	[4,5,14]
Lithuania	5 GW	6.4 GW	200 MW already added	1.70 %	3.90 %	Yes	[4,5,15]
Malta	0.35 GW	0	0.06 GW	17.14 %	17.14 %	Yes, financed from RRF and MFF	[5]
Netherlands	25.8 GW	23.2 GW	7.9 GW (forecast)	16.12 %	30.62 %		[5,9]
Poland	36.6 GW	21.8 GW	2 GW (forecast)	3.42 %	5.46 %	n.a.	[5]
Portugal	20.4 GW	12.4 GW	1 GW	3.00 %	4.90 %	No	[4]
Romania	8.3 GW	7.6 GW	240 MW or 480 MWh by 2025	2.5 % in 2025, 1.5 % in 2030 (without BESS addition later)	2.90 %	Yes, financed from RRF	[5,16]
Slovenia	3.5 GW	0.5 GW	850 MW	21.25 %	24.29 %	n.a.	[5]
Sweden	9.2 GW	23.4 GW	3.8 GW (forecast)	11.66 %	41.30 %	n.a.	[5,9]

*For Austria, Denmark, Croatia, Luxembourg, Latvia and Slovakia BESS data are not available in their NECP.

conclusions on the role of energy storage, it is necessary to employ detailed modelling on storage characteristics as well. These models, which are commonly referred to as Capacity Expansion Models (CEMs) [21], must be capable of accurately handling various storage technologies, which must be correctly characterised in detail, including round-trip efficiencies, storage capacity duration, losses, and deterioration. These models should be able to adequately represent the complexities associated with varying levels of vRES and cross-border capacity (CBC) within scenarios characterised by high levels of uncertainty. Furthermore, Solomon et al. [22] emphasised the importance of accurately characterising storage options in long-term planning models for the development of the power sector.

In their comprehensive review article, Jafari et al. [23] provide a detailed analysis of the role of storage technologies in the decarbonised power system, drawing upon insights from over 100 previous studies. The authors concluded that short-duration battery storage plays an important role in integrating solar energy and partially replacing peak-load plants. Most of the studies reviewed did not consider ambitious emission targets, such as the maximum 1.5 °C global temperature rise target. It was also found that the application of stringent decarbonisation policy is a driver of the deployment of energy storage technologies. Golombek et al. [24] highlighted the role of both energy storage and transmission developments in achieving the 2050 decarbonisation targets. The researchers found, based on their stochastic modelling, that there is a trade-off between investments in energy storage and transmission capacity, due to the increasing variability in electricity demand and supply resulting from the integration of vRES and electrification. They emphasised that the future cost evolution of battery storage and PV technologies is a driving factor in the future deployment of the power sector. The authors concluded that a 65–75 % share of vRES in the European power sector supply is necessary to achieve the EU’s 2050 decarbonisation goals. The authors project that between 198 and 326 GW of battery capacities will be required to reach the decarbonisation targets of Europe for 2050. In a previous assessment, Brouwer et al. [25] determined that up to 59 % of vRES expansion is necessary to achieve the European decarbonisation targets. However, they found that storage is too expensive to provide flexibility services without support, and that demand response, flexible gas units and curtailment options are the main contributors under market-based solutions in energy-only markets.

Several additional studies were conducted to assess the potential trade-offs between storage technologies and transmission expansion to provide flexibility services. However, the conclusions reached varied considerably, depending on the cost development assumptions and the modelling framework employed. Cebulla et al. [18] reached the conclusion that storage plays a crucial role in systems with high PV deployment rates, and that an appropriate level of storage capacity can reduce overall system cost in such systems. Cao et al. [26] found that transmission expansion is a more cost-effective solution to provide system adequacy than storage technologies. The application of the latter technology increases system cost by 2 % to achieve a similar level of adequacy at a pan-European level. Moser et al. [27] expanded the analysis of flexibility provision by incorporating new technology options, including solid oxide fuel cells, power-to-heat-to-power, and compressed air energy. They found that the future flexibility provision mix depends on both locational context and future cost development. Countries with a high share and potential for pumped hydro will utilise this cost-efficient option at a higher rate. Conversely, the Central European region and the UK are more likely to adopt a technology mix that includes pumped hydro, hydrogen underground storage and batteries. The study found that the ratio of PV and wind energy is also a significant factor in determining the shares of the various flexibility providers.

In a further development of the storage analysis, Victoria et al. [28] considered several additional sectors, including mobility and heating. The authors found that sector coupling enables deeper CO_2 reductions globally, as electric cars can replace a significant portion of stationary batteries. The authors concluded that the necessity for storage capacities will be significantly greater with higher than 80 % carbon reduction targets. In the case of a 95 % reduction target, for instance, battery and hydrogen storage capacities may be required at a level of 1.4 and 19.4 times the average hourly electricity demand, respectively. Smajila et al [29] included environmental factors, such as the carbon footprint of hybrid PV and battery systems, to find their optimal sizing and dispatch. Their results indicated that grid price signals, load variability and environmental factors can substantially change the optimal sizing of these hybrid systems.

Numerous studies have investigated the shares of batteries in renewable-intensive power sectors since 2010, when EU decarbonisation targets were less ambitious. Notably, Cebulla et al. [18] found that, on average, a 3 GW increase in energy storage capacity is required in Europe for every 1 %-point increase in vRES shares. Nevertheless, this requirement may increase to 4–9 GW if the proportion of photovoltaic (PV) energy in the renewable energy source (RES) mix is higher. Furthermore, they highlight that enhanced transmission expansion can serve to mitigate these ratios. The findings of Bertsch et al. [20] and Scholtz et al. [19] are in alignment with those of Cebulla et al. [18], which indicate that scenarios dominated by PV necessitate more storage capacity, while wind-dominated scenarios require increased transmission capacity.

This paper narrows its focus to a more straightforward question: what is the cost-minimising PV and battery storage penetration in 2030 on a European and Member State level, while calculating with the latest, ambitious emission reduction goals? It quantifies the impact of different PV-BESS capacity combinations considering a specific level of CBC expansion (according to ENTSO-E TYNDP plans [30]) and wind penetration (aligned with EU RePower targets) on the total cost of meeting the demand in the power sector in 2030 [31]. Its novelty compared to previous assessments, that it covers a much wider range of possible PV deployment and includes the costs of providing the ancillary services in the system. This latter one gets higher importance with the increasing vRES capacity deployment, also showing steadily increasing cost levels (ACER [32]) in many countries in the EU.

3. Methodology

3.1. Market modelling

To quantify the total system costs in the different scenarios, the European Power Market Model (EPMM) was employed. This is a unit commitment and economic dispatch model. The consumption of electricity is satisfied simultaneously in all modelled countries at a minimum system cost, taking into account the requirements for spinning reserve, the capacity constraints of the available power plants and the cross-border transmission capacities. The cost elements considered in the model include start-up and shut-down costs of the power plants, the costs of production (mainly fuel and CO2 costs) and the costs which occur to RES producers in the form of curtailment. The model uses technology-specific inputs on the generation side to predict the operating status of power plants every hour of the modelled weeks. This covers almost 3,500 conventional power plant units, as well as reservoir hydro plants besides vRES generation. It also predicts the volume of generation at operating units, the capacity set aside for upward and downward regulation, and the trade flows on cross-border interconnectors. In addition, it forecasts the wholesale market price of electricity and the price of upward and downward reserve capacities in each country. The generation-side information is updated with data from the last two years, making the model an appropriate tool for assessing the cost-optimality of scenarios with varying levels of vRES and battery storage deployment. On the demand side, electricity consumption growth follows an exogenous path with two endogenous mechanisms. The model has a low price elasticity of consumption, resulting in a limited reaction to price changes. On the other hand, demand side response (DSR) allows for peak shaving. In 2030, the assumption is that 8 % of the average hourly consumption within one modelled week could be relocated from the peak to valley period driven by price differences.

The model simultaneously optimises all 168 h of a modelled week, thereby determining the hours in which power plants operate and at what production level. The model is executed for 12 representative weeks of the given year, with each month represented by one week. The EPMM endogenously models 41 electricity markets in 38 countries across the ENTSO-E network. For a detailed description of the model, please refer to Pató et al. [33] and Szabo et al [34], its detailed mathematical formulation including the constraints and the objective function of the model is deposited at GITHUB [35].

3.2. Scenario setup

In the modelling process, apart from the installed PV and battery capacities, all scenarios were set up similarly, with the next EU target year of 2030 being modelled. The main inputs are derived primarily from the most recent forecasts issued by the European Commission and ENTSOs, as illustrated in the following Table 2.

All the combinations of five PV capacity and nine battery deployment set-ups were modelled. The latest ENTSOs National Trends scenario [30] for the EU27 predicts that PV installed capacity in 2030 will reach 354 GW. In the FIT55 documents, the EU target is 383 GW, which was increased by the RePower Europe policy to 592 GW ([31]). SolarPowerEurope, the European association of PV generators, has projected three potential development pathways for PV installed capacity in Europe [37]. In the most pessimistic scenario, the installed capacity is projected to reach 600 GW for the EU27, 736 GW in the moderate scenario, and 947 GW in the optimistic scenario.

Based on these values, the following PV scenarios were established: The very low PV scenario (353 GW in EU27) is identical to the ENTSOs National Trend (NT) scenario. Four further scenarios were created, in which PV capacities were multiplied by 1.5, 2.0, 2.5 and 3.0, respectively, corresponding to 353 – 530 – 706 – 803——1059 GW of PV capacity levels. These scenarios are referred to as Very low, Low, Medium, High and Very high PV scenarios. As the breakdown for countries is only available in the NT scenario, we have assumed that the distribution of

Table 2
Fuel prices, demand and cross-border capacity (CBC) information in the EPMM model.

	Methodology/value	Source
ARA Coal price, $/t	52	[36]
TTF gas price, €/MWh	31	REKK EGMM modelling
CO2 price, €/t	80	[37]
EU27 demand	Latest actual data with the growing rates based on FIT55 REF scenario	[38,39] and [40]
Trading capacity	Present grid capacities, plus the planned CBC	[30]

PV capacities will be the same in all scenarios. Furthermore, we have used the same rate of multipliers for all Member States.

The penetration of batteries is linked to wind and photovoltaic (PV) generation. A total of nine different penetration levels are assumed, ranging from zero to 20 % in increments of 2.5 %. The percentage indicates the proportion of battery production capacity relative to the sum of PV and wind installed capacities within a given country. As the capacity of wind power plants is fixed in the scenarios, the capacity of batteries is also changing in parallel with the capacity of solar power plants.

3.3. Annualised investment cost

To calculate the system cost change between the analysed scenarios, this study employs the following equation to determine the annualised investment cost:

$$INV = \frac{CAPEX}{1 - \frac{1}{(1+r)^t \times r}}, where \quad (1)$$

INV: Annualized investment cost, €/kW

CAPEX: Total investment cost, €/kW.

r: discount rate; %.

t: lifetime of the project, year.

The discount rate for both technologies is assumed to be 5 % in real terms, while the lifetime is 20 years for PV and battery storage. The CAPEX value is based on the average projected costs between 2023 and 2030. According to IRENA [41], the cost of PV capital expenditure (CAPEX) is 430 euros per kilowatt (€/kW), which equates to 31.5 euros per kilowatt per year (€/kW/year). In the case of storage systems, the model assumes a 2-hour battery technology with round-trip efficiency of 85 %. The projected CAPEX cost is 570 €/kW, based on Wesley et al. [42], which results in a 42.0 €/kW annualised investment cost.

4. Results and discussion

In addition to the variations in total system cost across the different scenarios, this section presents a concise overview of some of the most important findings to facilitate better understanding of how the main drivers influence the overall system cost. This section presents the changes in PV market values, followed by the values for battery utilization and PV curtailment. Finally, the results for total system costs are presented.

Fig. 1 below illustrates the connection between the PV market value

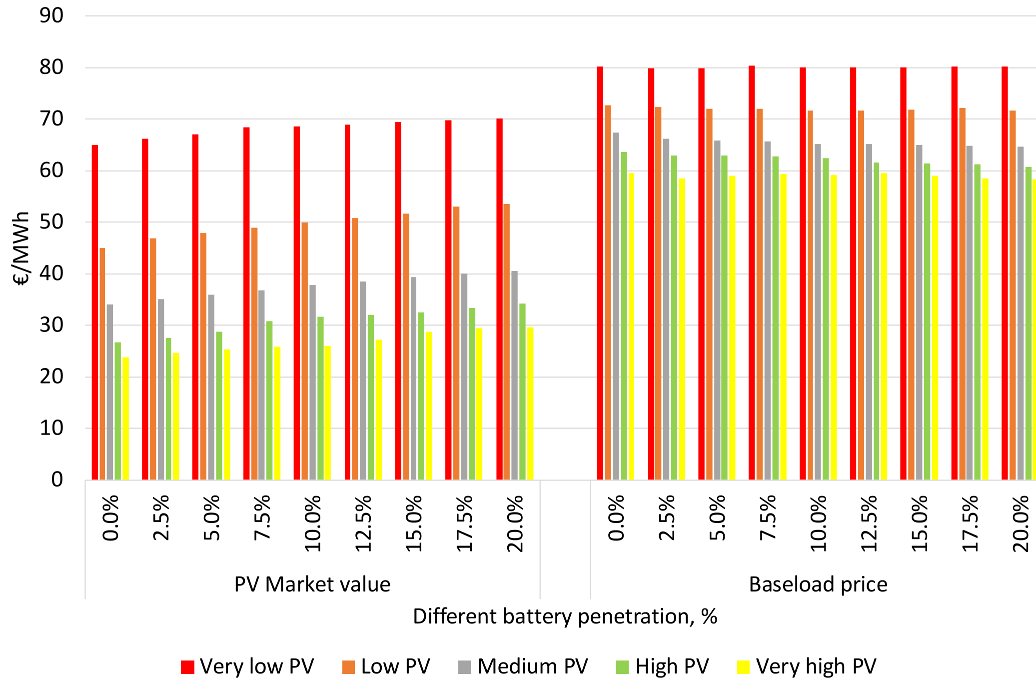

Fig. 1. The weighted average PV market value and baseload prices at different battery and PV penetration levels, €/MWh.

and the deployment level of PV and battery capacities. The market value of photovoltaic plants is defined as the weighted average of the wholesale price received by PV plants over a given period (e.g., a year). This price is calculated by dividing the total revenue generated by PV plants by the total production of electricity, as shown in

Higher PV penetration level has a strong impact on their market value, meaning they will receive less revenue per unit of production with higher deployment. But this impact is mitigated by higher deployment of battery storage, that helps to regain some of the economic value lost by the higher PV deployment.

Fig. 1 indicates that an additional 20 % battery penetration increases the PV market value by 10 to 15 % compared to the theoretical zero BESS level. The results demonstrate a pronounced cannibalization effect in the PV market value. Baseload prices – defined as the unweighted average of the 8760 h – also exhibit a downward trend in conjunction with an increase in the penetration of PV in the system. However, the magnitude of this decline is relatively modest. The impact of battery penetration on PV market value is positive, with almost no effect on baseload prices. This mechanism illustrates well, how battery storage helps the utilisation of stored solar energy at a later point in time, when it generates higher welfare to consumers.

4.1. Battery utilization

In this paper, the daily battery utilization rate is calculated as the sum of the absolute values of charging and discharging in a given day (MWh), divided by the battery capacity (MW) multiplied by 24 h. The greatest difference in battery utilization levels is observed between the

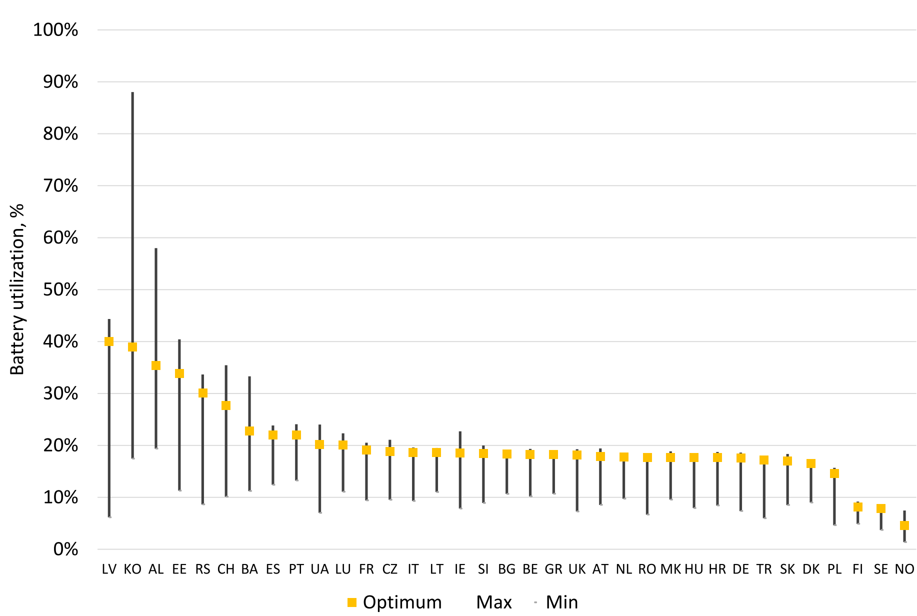

Fig. 2. Country specific battery utilization rates in the assessed scenarios, 2030.

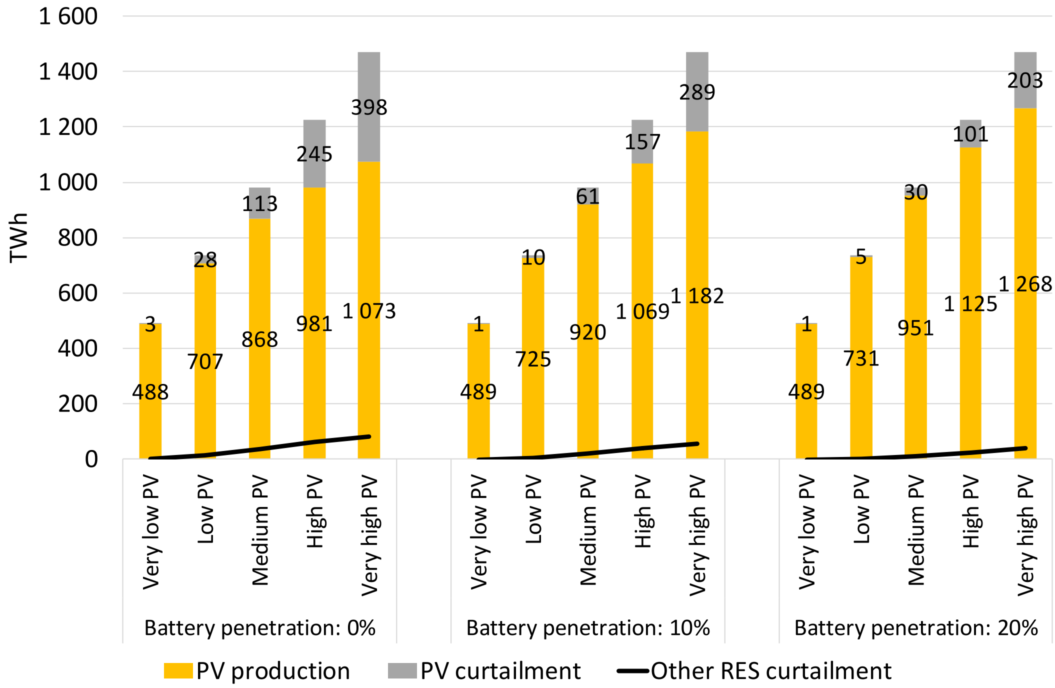

Fig. 3. PV production, PV curtailment and other RES production curtailment in the analysed countries, TWh, 2030.

Very Low and Low PV penetration scenarios, with utilization rates increasing by 0.4 cycles per day on average as illustrated by Fig. 8 in the Annex. After this level, the impact of increasing PV penetration is less pronounced. The modelling results indicate that the average utilization rate is approximately 20 %. This equates to approximately one cycle per day, which is a sustainable utilization rate from the perspective of battery lifetime. Therefore, assuming a 20-year battery lifetime is a realistic assumption in the modelled scenarios.

An analysis of the country-specific results on battery utilization reveals the existence of three groups of countries. Fig. 2 illustrates the utilization rates for the 45 modelled scenarios, also indicating where the optimal case is situated. The core continental Europe region exhibits a highly synchronized utilization pattern with a marginal variation of around 20 %. The modelled cost optimal case rate is on the high end of the distribution, showing that battery capacities are also optimally built. The uniform rates also suggest that utilization of batteries is not a 'national' issue, as they are mostly used for arbitrage – shaving the price peaks – batteries built in one country will help to reduce price volatility in other countries as well. The lower utilization rates in the Nordic countries (Sweden, Norway, Finland) indicate lower price volatility and greater availability of flexible hydro production. The third group of countries are the 'newcomers', i.e. Albania, Kosovo, and two Baltic states, with low battery penetration in 2030. Consequently, their high utilisation indicates they should consider increasing their battery storage targets.

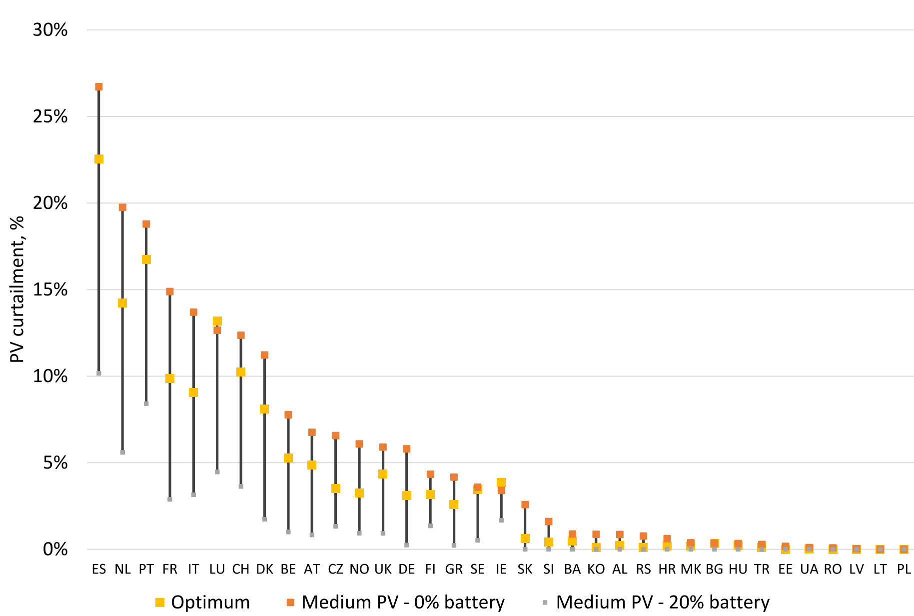

Fig. 4. PV curtailment in the assessed scenarios, 2030.

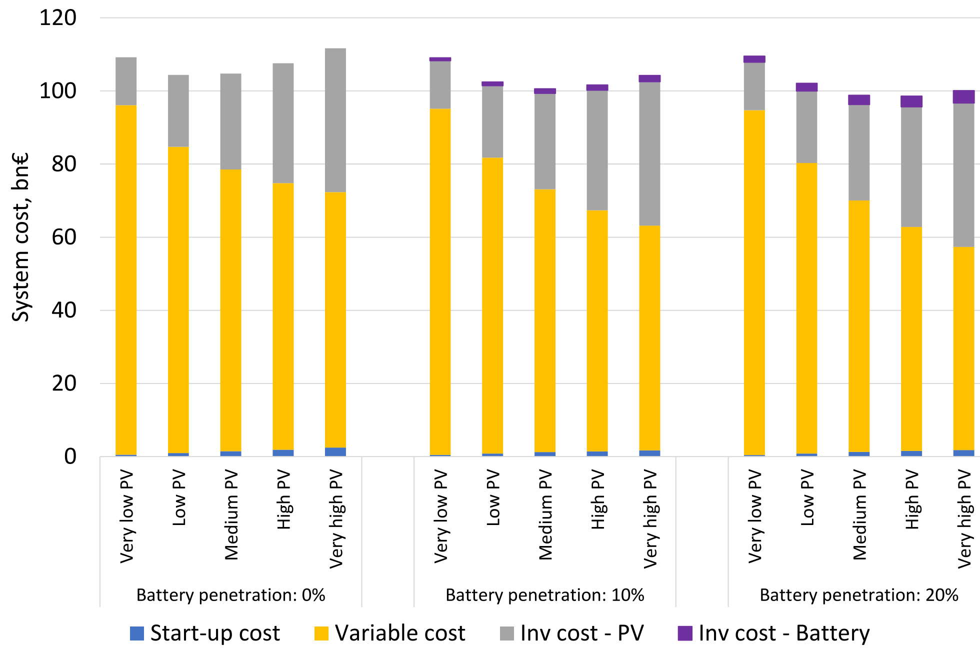

Fig. 5. Cost breakdown in the various scenarios, bn€.

4.2. PV curtailment

To understand differences between the scenarios, the changes in curtailment of PV plants and other renewables are also quantified. Fig. 3 illustrates the impacts of increasing battery deployment in scenarios with increasing PV penetration levels, also indicating the PV curtailment levels in the various scenarios.

Fig. 3 shows that 20 % of battery penetration reduces PV curtailment by 30 to 60 % in the various scenarios compared to the theoretical zero BESS cases. In the absence of new battery installations, the additional PV capacities in the Very High scenario will only be able to generate 64 % of their technical potential due to curtailments. This implies an increase in PV production of 90 TWh, accompanied by a corresponding increase in curtailment of 150 TWh. Furthermore, the increase in PV penetration results in a smaller increase in the curtailment of other RES producers. The penetration of batteries can help to reduce the curtailment of PV. In the Very High PV scenario, total solar curtailment shrinks by almost 50 % if a sufficient level of batteries is installed (20 % battery scenario). This result indicates that batteries' benefits primarily arise from reducing PV curtailment levels, rather than through reducing the price cannibalisation impacts.

With regard to the country-specific differences, high variation could be observed in the PV curtailment rates (see Fig. 4). The highest rates are observed in the countries with the highest PV deployment levels, like Spain and Portugal. Still, countries like the Netherlands and Denmark are also in this group, having a relatively high share of PV in their electricity mix in 2030. The middle-range countries group, which exhibits approximately a 5 % curtailment rate, is a mix of countries with substantial PV shares, such as Germany, Greece, Austria, and the Nordic countries, including Norway, Finland, and Sweden. The low curtailment group primarily comprises countries from East and Southeast European countries, including the Western Balkan, where curtailment rates are only a few percentage points. Many of them still have low PV deployment in 2030, and due to the high connectivity within the region, PV production could be exported to other countries without cross-border capacity constraints. Nevertheless, the rather high heterogeneity within these country groups indicates that many factors, including deployment rates of vRES, availability of flexible generation, price volatility, and cross-border trade influence curtailment levels. This complex issue requires further analysis in future research.

4.3. System cost

Having considered the principal alterations in PV and battery utilization, and their impact on one another, the changes in total system costs are calculated for varying PV and battery levels. As previously demonstrated, an increase in the deployment of solar plants is associated with a reduction in baseload prices, which in turn leads to a decrease in the total variable cost of serving the overall power demand. It is similarly anticipated that the integration of batteries will facilitate the integration of PVs, thereby further reducing the variable cost of generation. However, the installation of BESS and PV also entails significant investment costs. Consequently, in the subsequent calculation, both the cost of battery and PV plant installations are taken into account to gain a more comprehensive understanding and identify an optimal capacity combination of PV and battery.

The change in total system cost is calculated using the following equations:

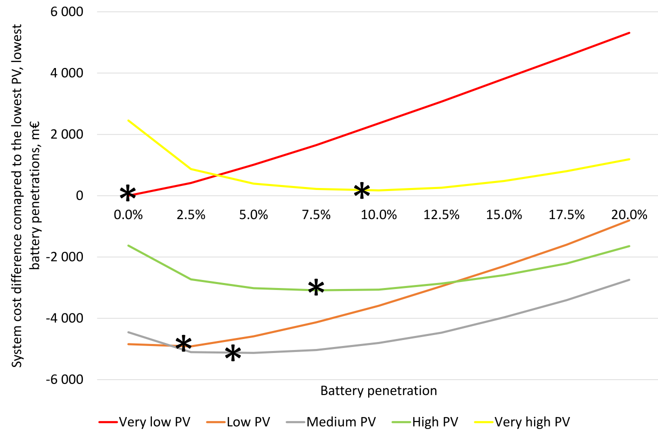

Fig. 6. System cost differences compared to the Very low PV and zero battery penetration scenario, m€ *Represents the lowest system cost in every PV deployment scenario.

$$\Delta \boldsymbol{SV} = \Delta \boldsymbol{VC} + \Delta \boldsymbol{INV}, \textbf{where} \tag{2}$$

- SV: Social value, m€
- VC: Variable cost of generation, including the variable OPEX, fuel and CO_2 cost, m€
- INV: Annualized investment cost, m€

$$\boldsymbol{VC} = \sum_{i=1}^{n} \boldsymbol{MC_i} \times \boldsymbol{Q_{nonRES;i}} + \sum_{i=1}^{n} \boldsymbol{SC_i} \times \boldsymbol{QS_i}, \textbf{where} \tag{3}$$

- MC_i is the marginal cost of non-RES i producers, €/MWh
- $Q_{nonRES,i}$ is the yearly produced electricity by producer I; MWh
- n is the total number of non-RES producers
- SC is the start-up cost of non-RES i producers; €/MW
- QS is the number of start-ups of non-RES i procures per year

$$-\Delta \sum_{i=1}^{n} \boldsymbol{Q_{nonRES,i}} = \Delta \sum_{j=1}^{m} \boldsymbol{Q_{PV\_pot,j}} - \Delta \sum_{j=1}^{m} \boldsymbol{Q_{PV\_curt,j}} + \Delta \sum_{j=1}^{m} \boldsymbol{Q_{othRES,j}}, \textit{where} \tag{3}$$

- $Q_{PV\_pt,\ j}$ is the yearly PV maximum generation (installed capacity availability factor) in country j; MWh
- $Q_{PV\_curt,\ j}$ is the yearly curtailed PV production in country j; MWh
- $Q_{othRES,\ j}$ is the yearly production by other RES, non-PV generators in country j, MWh
- $Q_{nonRES,\ j}$ is the yearly production by non-RES generators in country j; MWh

Costs are quantified in four main categories: start-up costs, further variable generation costs, PV investment and battery investment costs and shown in Fig. 5. Start-up costs are insignificant in comparison to the overall expenditure, although they tend to increase in parallel with an increase in the penetration of photovoltaic (PV) technology. The incorporation of a battery into the system can serve to offset this effect. Serving the required level of reserve capacities is incorporated in the variable cost part, as reserve capacities dedicate part of their running cost to this service.

The annualised investment cost of battery and PV can range from approximately 10 % if PV and battery penetration is low, to close to 40 % of total costs in the Very high PV + 20 % battery scenario. It can be observed that there is a global (European) cost minimum within the range of PV and battery capacities that have been analysed. This is illustrated in greater detail for all modelled scenarios in Fig. 6.

The important message of Fig. 6 is that a European optimum exists at

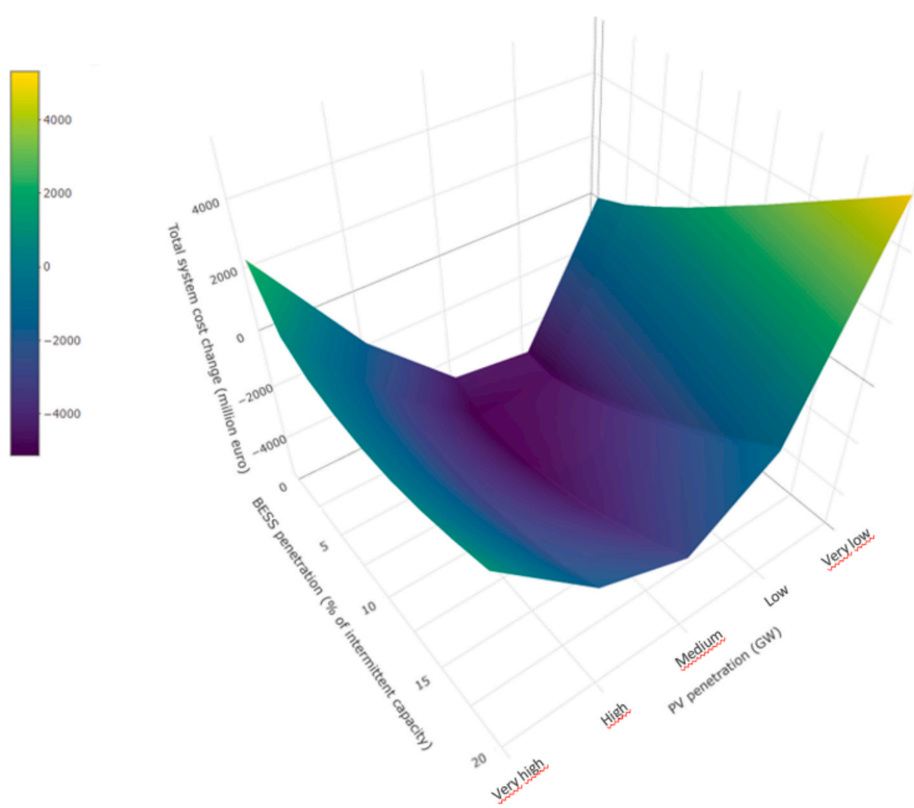

Fig. 7. Total system costs for the modelled PV – BESS combinations.

around 5 % BESS capacity, where this share represents the battery to vRES capacity ratio. The medium scenario in this case means roughly 15 % higher PV deployment than the present RePower target for the EU. Reduced wholesale prices and minimised curtailment levels of PV installations drive the costs to the minimum in this scenario. The second finding is that the optimal battery penetration depends on the PV penetration: the higher the PV penetration, the higher the optimal battery penetration.

It is also observable that the optimal battery penetration is below 10 % in all the scenarios that have been analysed. In all cases, high and very high PV penetration is more costly from a total system cost perspective than the medium PV cases, regardless of the battery penetration level.. These values can be considered an upper boundary, as further cross-border capacity assumptions or a higher level of available demand-side response could further reduce the necessity for BESS in the European power system. Fig. 7 illustrates this cost optimality in a three-dimensional pane, showing the minimum cost of the system in all the modelled PV-BESS combinations for 2030.

Changes in the system cost are also checked in a set of various sensitivity runs, where the CAPEX cost of the battery storage and the PV plants are varied in a broader range around the assumed central value. The cost range is tested at 50 % lower and higher levels, with 10 % increments applied for both technologies. With the varied CAPEX costs, the new optimum changes, and we have assessed the impacts on the optimal level of installed PV and battery capacities. Changes in the two CAPEX costs represent distinct changes in the optimality. In the case of PV technology, portfolio changes are linear, meaning both PV and battery capacities vary in the expected opposite direction of the CAPEX change. Battery CAPEX impacts the system differently. Higher CAPEX reduces battery and PV capacity levels in the optimality case, but reducing battery cost does not change the optimal PV level in the European power system. It underlines the supportive role of battery storage: a higher level of PV penetration (driven by the lower CAPEX) needs a higher level of storage to keep PV integrated into the power system, meaning a lower level of curtailment and balancing costs. However, a lower battery storage cost level alone would have a more limited impact on the optimal PV deployment levels. These changes are illustrated in Fig. 9 in the Annex.

5. Conclusions

Transformation of the European power sector is ongoing and characterised by significant dynamism in variable RES deployment. This is evidenced by the rapid installation of solar plants, which has induced a corresponding need for flexibility. Nevertheless, the optimal method for addressing this need remains uncertain. The exponential growth of photovoltaic plants requires strong integration measures, including implementing short-term storage solutions. Due to their cost reduction, battery energy storage systems have gained momentum in recent years. This paper quantified the overall system costs of 45 scenarios where battery energy storage system (BESS) penetration is linked to photovoltaic (PV) capacities.

The analysis indicates a pronounced cannibalization effect on the PV market value by 2030 in case the desired capacity levels of the 2030 EU targets are achieved. This effect can be moderated by higher storage capacities, where the installation of BESS can facilitate the integration of PV plants by an arbitrage option as well as providing flexible reserve capacities in the power system. This is also verified by the modelled battery utilization patterns, which demonstrate that higher solar penetration has a positive impact on battery utilization. Furthermore, batteries can assist to reduce the curtailment of PV energy, which impact becomes increasingly prevalent as the penetration threshold is exceeded.

The modelling results indicate that the optimal battery penetration level depends on the solar deployment level. The requirement for storage systems increases proportionately to the installed capacity of photovoltaic panels. From the perspective of total system cost, the least cost solution for Europe is the medium PV penetration scenario, which involves approximately 707 GW of PV capacity and 5 % of the total installed intermittent capacity dedicated to BESS by 2030. The optimal battery penetration level is consistently below 10 % measured in relation to the intermittent renewable capacity deployment. When other characteristics of the system are maintained at their reference levels (e.g. net transfer capacities, wind capacities, demand), it is observed that further PV penetration induces greater costs than benefits, even when combined with significant BESS capacities. Therefore, countries must carefully design their battery deployment targets, as a higher level of battery storage means higher investment costs that are not balanced out by the additional cost savings of the flexibility provision. Countries having a higher share of other storage solutions (e.g. pump hydro) should consider even lower level of battery storage than the modelled average figure.

The analysis of the country-specific results reveals a high degree of heterogeneity in Europe concerning PV curtailment levels, which range from close to zero to 20 %. This indicates that besides PV deployment levels, other market factors, such as the availability of flexible capacities, level of price volatility and cross-border trade, are important contributors to this variation. In contrast, daily battery utilization rates are quite homogenous amongst most Member States, with small variations around 20 % rate representing an optimal cycle in battery utilisation. Nordic countries, such as Norway, Sweden, and Finland, are exceptions to this rule, as the flexible hydro capacities in Nordpool reduce the need for battery storage services. The opposite group of countries are the 'newcomers' with lower ambitions in their battery targets for 2030. Due to their low capacity levels, battery storage utilization rates are higher in this cluster, reaching higher than 30 %. The homogeneity in utilization rates in the optimal scenario also suggests that battery services could be efficiently shared amongst European countries if sufficient cross-border capacities allow it.

Caveats and future work

The analysis contributes to the existing literature by modelling more ambitious decarbonisation scenarios than previous studies, representing the latest, more ambitious EU policy directions set out in the RePower EU plans and even going beyond in PV capacity levels. The results indicate that in solar capacities, a 15 % higher deployment is still cost optimal compared to the RePower targets, if balanced with optimal battery storage. The assessment provides specific optimal values for PV and BESS deployment from the perspective of the European power system, based on system cost minimisation. The results on the optimal mix of battery-PV deployment levels can assist policymakers in establishing the most effective incentives and regulations in the context of the rapidly evolving European electricity sector.

The impacts of varying transmission capacity levels and the role of other intermittent technologies, such as wind energy, can be further investigated in a future study. Given the complexity and ongoing evolution of the power sector, it is important to analyse further new technologies and solutions such as hydrogen and demand side management options to explore how the power of the future can be delivered in the most cost-efficient way.

The modelling framework does not include the analysis of any technological breakthrough in the storage technologies, nor any substantial change in the regulatory environment. These can have a substantial impact on the results. However, the results can help national regulators and policymakers identify regulatory needs, e.g., in the target setting of battery storage levels corresponding to variable RES developments.

CRediT authorship contribution statement

Enikő Kácsor: Writing – original draft, Methodology, Data curation, Conceptualization. **András Mezősi:** Writing – original draft, Software, Formal analysis, Conceptualization. **László Szabó:** Writing – review & editing, Writing – original draft, Supervision, Investigation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Laszlo Szabo and Andras Mezosi reports financial support was provided by National Research Development and Innovation Office. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Annex 1.

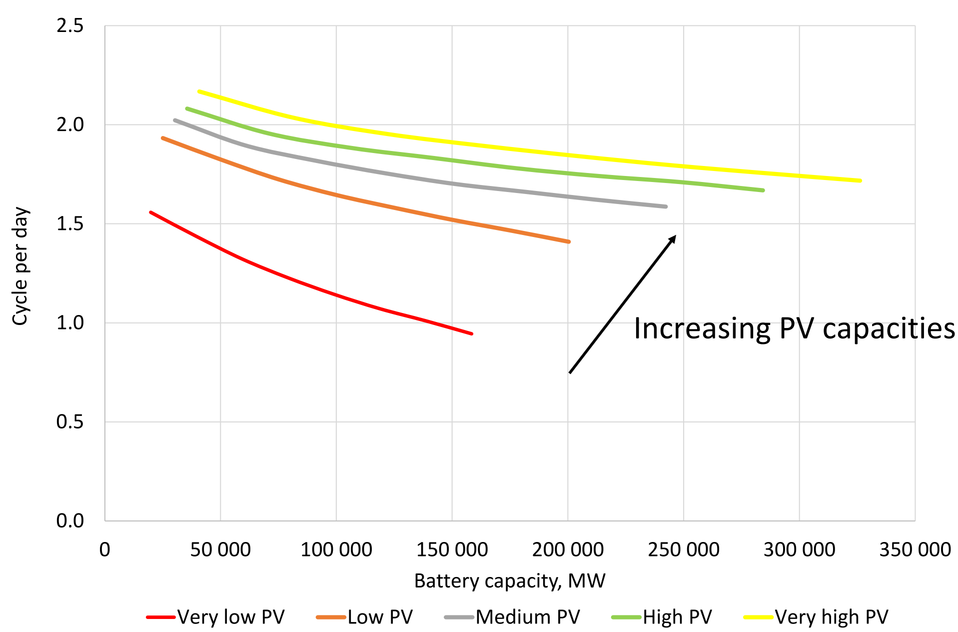

Fig. 8. The average battery utilisation rate in different scenarios of battery and PV penetration.

Annex 2.

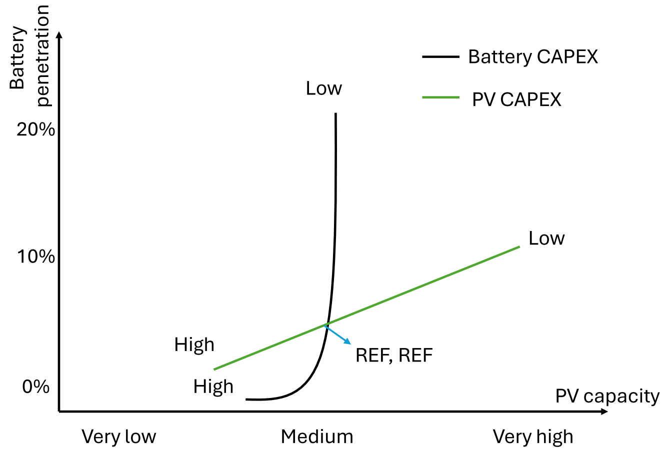

Fig. 9. Sensitivity assessment of PV and battery CAPEX costs.

*Low sensitivity value: REF CAPEX cost*0.5; High sensitivity value: REF CAPEX cost *1.5.

Annex 3:. Curtailment by technologies

PV curtailment, GWh

		PV penetration				
		Very low PV	Low PV	Medium PV	High PV	Very high PV
Battery penetration, %	0.0 %	2,899	28,156	113,293	244,947	397,986
	2.5 %	2,410	21,659	96,684	220,244	368,424
	5.0 %	2,109	16,916	83,240	198,185	339,991
	7.5 %	1,643	13,302	71,728	177,627	314,869
	10.0 %	1,455	10,493	61,098	156,874	288,745
	12.5 %	1,473	8,827	50,628	140,367	266,958
	15.0 %	1,281	6,945	43,005	126,207	243,504
	17.5 %	1,056	5,590	35,629	111,687	225,373
	20.0 %	994	4,777	30,172	100,878	203,235

Non-PV RES curtailment, GWh

		PV penetration				
		Very low PV	Low PV	Medium PV	High PV	Very high PV
Battery penetration, %	0.0 %	4,844	19,722	42,288	65,836	85,428
	2.5 %	3,814	17,364	38,256	58,653	78,189
	5.0 %	3,091	14,140	34,065	52,606	73,104
	7.5 %	3,015	11,657	29,833	47,256	67,296
	10.0 %	2,779	9,889	25,277	43,570	61,728
	12.5 %	2,268	8,211	23,310	38,787	55,647
	15.0 %	2,214	7,347	19,800	35,062	52,560
	17.5 %	2,090	6,296	17,445	30,514	48,114
	20.0 %	1,851	5,435	14,988	28,441	42,623

Total RES curtailment, GWh

		PV penetration				
		Very low PV	Low PV	Medium PV	High PV	Very high PV
Battery penetration, %	0.0 %	7,743	47,878	155,580	310,783	483,414
	2.5 %	6,224	39,023	134,940	278,897	446,613
	5.0 %	5,199	31,056	117,306	250,791	413,095
	7.5 %	4,658	24,959	101,562	224,883	382,165
	10.0 %	4,234	20,382	86,375	200,444	350,473
	12.5 %	3,742	17,038	73,939	179,155	322,605
	15.0 %	3,495	14,293	62,806	161,269	296,063
	17.5 %	3,146	11,885	53,074	142,202	273,488
	20.0 %	2,845	10,213	45,160	129,319	245,858

Non-PV RES curtailment compared to the total RES curtailment, %

		PV penetration				
		Very low PV	Low PV	Medium PV	High PV	Very high PV
Battery penetration, %	0.0 %	62.6 %	41.2 %	27.2 %	21.2 %	17.7 %
	2.5 %	61.3 %	44.5 %	28.4 %	21.0 %	17.5 %
	5.0 %	59.4 %	45.5 %	29.0 %	21.0 %	17.7 %
	7.5 %	64.7 %	46.7 %	29.4 %	21.0 %	17.6 %
	10.0 %	65.6 %	48.5 %	29.3 %	21.7 %	17.6 %
	12.5 %	60.6 %	48.2 %	31.5 %	21.7 %	17.2 %
	15.0 %	63.3 %	51.4 %	31.5 %	21.7 %	17.8 %
	17.5 %	66.4 %	53.0 %	32.9 %	21.5 %	17.6 %
	20.0 %	65.1 %	53.2 %	33.2 %	22.0 %	17.3 %

Annex 4:. Main input and output of some selected scenarios

Scenario: Very low PV — 0 % battery

	Capacity mix, MW																
	Coal and lignite	Natural gas and other fossil	Nuclear	PV	Wind	Run-of river	Hydro Storage	Other RES	Pumped storage	Battery	DSM	Baseload price, €/MWh	PV market value, €/MWh	PV production, MWh	PV curtailment, MWh	PV curtailment ratio, %	Battery utilization, %
AL	0	0	0	500	13	532	1,723	6	0	0	83	101.7	90.8	664	0	0.0 %	0.0 %
AT	0	4,262	0	12,000	6,124	5,897	3,161	947	6,678	0	699	100.2	85.6	14,048	1	0.0 %	0.0 %
BA	1,800	0	0	350	486	296	1,482	7	1,551	0	120	101.5	90.8	459	0	0.0 %	0.0 %
BE	0	3,989	0	10,400	7,595	106	0	880	1,307	0	990	127.8	88.7	10,983	12	0.1 %	0.0 %
BG	60	2,282	2,080	3,216	1,106	543	1,826	210	1,404	0	326	99.8	88.5	4,474	0	0.0 %	0.0 %
BY	0	2,403	2,388	309	65	46	0	136	0	0	384	95.7	89.7	319	0	0.0 %	0.0 %
CH	0	589	2,715	9,800	232	5,531	10,816	1,197	4,914	0	568	66.3	51.3	11,881	13	0.1 %	0.0 %
CZ	6,264	2,129	4,164	8,159	945	360	753	1,119	1,175	0	656	100.9	85.2	8,600	0	0.0 %	0.0 %
DE	24,537	26,297	0	96,140	82,405	3,841	1,429	8,972	6,442	0	5,608	99.5	84.0	80,825	0	0.0 %	0.0 %
DK	140	819	0	6,467	10,485	7	0	2,040	0	0	441	91.0	76.6	6,606	25	0.4 %	0.0 %
EE	395	281	0	415	1,254	4	0	241	0	0	97	91.5	88.9	434	0	0.0 %	0.0 %
ES	92	32,129	5,315	45,704	50,928	1,239	13,544	2,442	6,166	0	2,623	54.4	35.6	68,893	2,320	3.3 %	0.0 %
FI	1,804	2,506	4,622	1,498	6,295	3,225	0	2,509	0	0	908	63.5	63.2	1,410	20	1.4 %	0.0 %
FR	0	9,324	57,217	43,781	26,498	11,196	8,911	2,534	5,589	0	4,348	50.2	33.7	54,840	71	0.1 %	0.0 %
GR	660	6,496	0	7,471	6,546	352	2,673	344	1,379	0	581	98.4	85.8	10,138	0	0.0 %	0.0 %
HR	210	1,344	0	750	1,614	434	1,468	180	822	0	202	101.9	90.6	903	0	0.0 %	0.0 %
HU	0	3,195	2,026	6,454	369	39	28	767	0	0	551	101.9	90.3	7,964	0	0.0 %	0.0 %
IE	0	3,829	0	600	8,816	217	22	165	2,152	0	432	72.0	67.2	614	3	0.5 %	0.0 %
IT	5,190	50,724	0	52,000	13,766	10,507	4,441	4,035	8,409	0	3,274	91.7	75.9	73,292	23	0.0 %	0.0 %
KO	540	0	0	339	360	53	74	19	0	0	70	101.7	90.7	475	0	0.0 %	0.0 %
LT	0	655	0	1,250	1,905	133	5	152	900	0	122	92.2	89.6	1,236	0	0.0 %	0.0 %
LU	0	293	0	608	237	25	11	44	1,296	0	67	99.5	84.8	648	7	1.0 %	0.0 %
LV	6	1,244	0	109	428	1,689	0	201	0	0	78	91.5	89.3	111	0	0.0 %	0.0 %
MD	1,600	1,332	0	17	100	89	0	12	0	0	47	99.8	89.3	20	0	0.0 %	0.0 %
ME	225	0	0	32	225	355	381	0	0	0	37	101.5	90.5	41	0	0.0 %	0.0 %
MK	0	383	0	563	85	13	720	10	333	0	80	101.7	90.9	798	0	0.0 %	0.0 %
NL	274	10,263	515	27,264	13,824	38	0	687	0	0	1,291	127.7	88.1	26,588	12	0.0 %	0.0 %
NO	0	1,082	0	600	9,391	5,801	25,385	49	1,392	0	1,279	58.4	58.6	565	0	0.1 %	0.0 %
PL	19,956	5,308	0	5,114	17,043	453	493	2,506	2,519	0	1,829	104.2	96.5	5,286	0	0.0 %	0.0 %
PT	0	4,033	0	7,761	9,022	2,973	1,576	1,006	4,515	0	542	55.9	39.2	11,895	303	2.5 %	0.0 %
RO	330	3,353	2,813	5,054	5,026	2,870	3,467	382	1,258	0	698	100.1	89.5	6,510	0	0.0 %	0.0 %
RS	3,096	1,255	0	235	1,169	2,064	476	50	628	0	331	101.5	90.9	318	0	0.0 %	0.0 %
SE	0	1,800	7,117	7,338	19,376	16,334	71	4,016	91	0	1,303	60.8	59.6	7,185	24	0.3 %	0.0 %
SI	654	589	688	1,866	175	1,182	0	133	625	0	162	101.9	90.3	2,254	0	0.0 %	0.0 %
SK	0	1,022	4,142	1,188	126	411	1,228	300	1,017	0	297	100.1	89.3	1,386	0	0.0 %	0.0 %
TR	23,891	15,976	5,920	17,500	18,574	7,755	20,536	2,300	1,400	0	3,299	45.2	39.6	28,357	0	0.0 %	0.0 %
UA	6,991	2,276	13,835	10,374	5,400	195	5,051	93	1,563	0	1,408	99.6	88.3	11,733	0	0.0 %	0.0 %
UK	559	22,276	6,848	23,408	42,422	1,914	0	17,413	5,033	0	2,914	69.3	59.2	24,751	65	0.3 %	0.0 %

Scenario: Very low PV — 20 % battery

	Capacity mix, MW																
	Coal and lignite	Natural gas and other fossil	Nuclear	PV	Wind	Run-of river	Hydro Storage	Other RES	Pumped storage	Battery	DSM	Baseload price, €/MWh	PV market value, €/MWh	PV production, MWh	PV curtailment, MWh	PV curtailment ratio, %	Battery utilization, %
AL	0	0	0	500	13	532	1,723	6	0	103	83	101.0	93.1	664	0	0.0 %	27.2 %
AT	0	4,262	0	12,000	6,124	5,897	3,161	947	6,678	3,625	699	99.5	91.2	14,049	0	0.0 %	8.5 %
BA	1,800	0	0	350	486	296	1,482	7	1,551	167	120	101.0	93.1	459	0	0.0 %	11.2 %
BE	0	3,989	0	10,400	7,595	106	0	880	1,307	3,599	990	113.2	93.8	10,995	0	0.0 %	10.2 %
BG	60	2,282	2,080	3,216	1,106	543	1,826	210	1,404	864	326	99.1	90.2	4,474	0	0.0 %	10.7 %
BY	0	2,403	2,388	309	65	46	0	136	0	75	384	91.4	89.8	319	0	0.0 %	0.0 %
CH	0	589	2,715	9,800	232	5,531	10,816	1,197	4,914	2,006	568	66.7	53.9	11,894	0	0.0 %	10.1 %
CZ	6,264	2,129	4,164	8,159	945	360	753	1,119	1,175	1,821	656	100.1	90.8	8,600	0	0.0 %	9.5 %
DE	24,537	26,297	0	96,140	82,405	3,841	1,429	8,972	6,442	35,709	5,608	99.0	89.7	80,825	0	0.0 %	7.3 %
DK	140	819	0	6,467	10,485	7	0	2,040	0	3,390	441	91.7	83.6	6,629	1	0.0 %	9.0 %
EE	395	281	0	415	1,254	4	0	241	0	334	97	89.3	90.0	434	0	0.0 %	11.3 %

(*continued on next page*)

(*continued*)

Scenario: Very low PV – 20 % battery

	Capacity mix, MW											Baseload price, €/MWh	PV market value, €/MWh	PV production, MWh	PV curtailment, MWh	PV curtailment ratio, %	Battery utilization, %
	Coal and lignite	Natural gas and other fossil	Nuclear	PV	Wind	Run-of river	Hydro Storage	Other RES	Pumped storage	Battery	DSM						
ES	92	32,129	5,315	45,704	50,928	1,239	13,544	2,442	6,166	19,326	2,623	54.2	42.4	70,346	867	1.2 %	12.4 %
FI	1,804	2,506	4,622	1,498	6,295	3,225	0	2,509	0	1,559	908	65.2	67.0	1,418	13	0.9 %	4.9 %
FR	0	9,324	57,217	43,781	26,498	11,196	8,911	2,534	5,589	14,056	4,348	51.1	36.6	54,911	0	0.0 %	9.4 %
GR	660	6,496	0	7,471	6,546	352	2,673	344	1,379	2,803	581	97.9	88.6	10,138	0	0.0 %	10.7 %
HR	210	1,344	0	750	1,614	434	1,468	180	822	473	202	101.2	93.0	903	0	0.0 %	8.4 %
HU	0	3,195	2,026	6,454	369	39	28	767	0	1,365	551	101.2	92.7	7,964	0	0.0 %	7.9 %
IE	0	3,829	0	600	8,816	217	22	165	2,152	1,883	432	73.9	69.8	616	0	0.1 %	7.8 %
IT	5,190	50,724	0	52,000	13,766	10,507	4,441	4,035	8,409	13,153	3,274	92.5	82.8	73,315	0	0.0 %	9.3 %
KO	540	0	0	339	360	53	74	19	0	140	70	101.0	93.0	475	0	0.0 %	18.6 %
LT	0	655	0	1,250	1,905	133	5	152	900	631	122	90.0	90.4	1,236	0	0.0 %	11.0 %
LU	0	293	0	608	237	25	11	44	1,296	169	67	99.0	90.3	655	0	0.0 %	11.1 %
LV	6	1,244	0	109	428	1,689	0	201	0	107	78	89.3	90.2	111	0	0.0 %	6.1 %
MD	1,600	1,332	0	17	100	89	0	12	0	23	47	99.4	91.2	20	0	0.0 %	21.9 %
ME	225	0	0	32	225	355	381	0	0	51	37	101.0	92.9	41	0	0.0 %	34.8 %
MK	0	383	0	563	85	13	720	10	333	130	80	101.0	93.2	798	0	0.0 %	9.6 %
NL	274	10,263	515	27,264	13,824	38	0	687	0	8,218	1,291	113.2	93.7	26,600	0	0.0 %	9.7 %
NO	0	1,082	0	600	9,391	5,801	25,385	49	1,392	1,998	1,279	61.4	62.7	565	1	0.1 %	1.4 %
PL	19,956	5,308	0	5,114	17,043	453	493	2,506	2,519	4,431	1,829	102.3	97.5	5,286	0	0.0 %	5.0 %
PT	0	4,033	0	7,761	9,022	2,973	1,576	1,006	4,515	3,357	542	54.4	42.5	12,094	104	0.9 %	13.2 %
RO	330	3,353	2,813	5,054	5,026	2,870	3,467	382	1,258	2,016	698	99.6	91.5	6,510	0	0.0 %	6.7 %
RS	3,096	1,255	0	235	1,169	2,064	476	50	628	281	331	101.0	93.1	318	0	0.0 %	8.6 %
SE	0	1,800	7,117	7,338	19,376	16,334	71	4,016	91	5,343	1,303	63.3	64.6	7,203	6	0.1 %	3.7 %
SI	654	589	688	1,866	175	1,182	0	133	625	408	162	101.2	92.8	2,254	0	0.0 %	8.9 %
SK	0	1,022	4,142	1,188	126	411	1,228	300	1,017	263	297	99.6	91.8	1,386	0	0.0 %	8.5 %
TR	23,891	15,976	5,920	17,500	18,574	7,755	20,536	2,300	1,400	7,215	3,299	51.5	48.4	28,357	0	0.0 %	6.0 %
UA	6,991	2,276	13,835	10,374	5,400	195	5,051	93	1,563	3,155	1,408	99.2	90.5	11,733	0	0.0 %	7.0 %
UK	559	22,276	6,848	23,408	42,422	1,914	0	17,413	5,033	13,166	2,914	72.0	64.1	24,814	2	0.0 %	7.3 %

Scenario: Very high PV – 0 % battery

	Capacity mix, MW											Baseload price, €/MWh	PV market value, €/MWh	PV production, MWh	PV curtailment, MWh	PV curtailment ratio, %	Battery utilization, %
	Coal and lignite	Natural gas and other fossil	Nuclear	PV	Wind	Run-of river	Hydro Storage	Other RES	Pumped storage	Battery	DSM						
AL	0	0	0	1,500	13	532	1,723	6	0	0	83	83.5	38.0	1,795	197	9.9 %	0.0 %
AT	0	4,262	0	36,000	6,124	5,897	3,161	947	6,678	0	699	79.8	31.3	33,142	9,006	21.4 %	0.0 %
BA	1,800	0	0	1,050	486	296	1,482	7	1,551	0	120	83.1	38.0	1,257	120	8.7 %	0.0 %
BE	0	3,989	0	31,200	7,595	106	0	880	1,307	0	990	109.6	30.7	24,487	8,498	25.8 %	0.0 %
BG	60	2,282	2,080	9,649	1,106	543	1,826	210	1,404	0	326	80.1	33.7	11,868	1,554	11.6 %	0.0 %
BY	0	2,403	2,388	927	65	46	0	136	0	0	384	80.0	58.7	956	2	0.2 %	0.0 %
CH	0	589	2,715	29,400	232	5,531	10,816	1,197	4,914	0	568	47.4	23.4	25,104	10,578	29.6 %	0.0 %
CZ	6,264	2,129	4,164	24,476	945	360	753	1,119	1,175	0	656	80.7	30.3	20,646	5,154	20.0 %	0.0 %
DE	24,537	26,297	0	288,419	82,405	3,841	1,429	8,972	6,442	0	5,608	78.9	29.2	180,438	62,036	25.6 %	0.0 %
DK	140	819	0	19,401	10,485	7	0	2,040	0	0	441	69.9	26.3	14,921	4,970	25.0 %	0.0 %
EE	395	281	0	1,245	1,254	4	0	241	0	0	97	74.9	54.8	1,278	23	1.8 %	0.0 %
ES	92	32,129	5,315	137,112	50,928	1,239	13,544	2,442	6,166	0	2,623	−43.6	−295.8	127,270	86,369	40.4 %	0.0 %
FI	1,804	2,506	4,622	4,494	6,295	3,225	0	2,509	0	0	908	38.5	24.9	3,954	338	7.9 %	0.0 %
FR	0	9,324	57,217	131,343	26,498	11,196	8,911	2,534	5,589	0	4,348	37.8	18.0	112,067	52,665	32.0 %	0.0 %
GR	660	6,496	0	22,413	6,546	352	2,673	344	1,379	0	581	79.2	30.9	23,071	7,344	24.1 %	0.0 %
HR	210	1,344	0	2,250	1,614	434	1,468	180	822	0	202	83.3	37.5	2,548	161	5.9 %	0.0 %
HU	0	3,195	2,026	19,362	369	39	28	767	0	0	551	82.6	35.0	21,382	2,508	10.5 %	0.0 %
IE	0	3,829	0	1,800	8,816	217	22	165	2,152	0	432	56.3	43.2	1,710	139	7.5 %	0.0 %
IT	5,190	50,724	0	156,000	13,766	10,507	4,441	4,035	8,409	0	3,274	76.9	27.0	149,112	70,834	32.2 %	0.0 %
KO	540	0	0	1,017	360	53	74	19	0	0	70	83.5	37.9	1,288	137	9.6 %	0.0 %

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	Capacity mix, MW											Baseload price, €/MWh	PV market value, €/MWh	PV production, MWh	PV curtailment, MWh	PV curtailment ratio, %	Battery utilization, %
	Scenario: Very high PV − 0 % battery																
LT	0	655	0	3,750	1,905	133	5	152	900	0	122	75.5	55.8	3,683	24	0.6 %	0.0 %
LU	0	293	0	1,824	237	25	11	44	1,296	0	67	78.9	30.5	1,493	471	24.0 %	0.0 %
LV	6	1,244	0	326	428	1,689	0	201	0	0	78	74.9	55.4	323	8	2.5 %	0.0 %
MD	1,600	1,332	0	52	100	89	0	12	0	0	47	80.4	36.0	47	13	22.0 %	0.0 %
ME	225	0	0	95	225	355	381	0	0	0	37	83.5	37.3	104	18	15.1 %	0.0 %
MK	0	383	0	1,689	85	13	720	10	333	0	80	83.5	38.9	2,198	195	8.1 %	0.0 %
NL	274	10,263	515	81,791	13,824	38	0	687	0	0	1,291	109.4	29.4	51,886	27,915	35.0 %	0.0 %
NO	0	1,082	0	1,800	9,391	5,801	25,385	49	1,392	0	1,279	27.1	20.9	1,466	230	13.5 %	0.0 %
PL	19,956	5,308	0	15,342	17,043	453	493	2,506	2,519	0	1,829	97.8	76.5	15,842	16	0.1 %	0.0 %
PT	0	4,033	0	23,284	9,022	2,973	1,576	1,006	4,515	0	542	−38.8	−287.2	23,448	13,146	35.9 %	0.0 %
RO	330	3,353	2,813	15,162	5,026	2,870	3,467	382	1,258	0	698	80.5	35.7	18,518	1,011	5.2 %	0.0 %
RS	3,096	1,255	0	705	1,169	2,064	476	50	628	0	331	83.1	38.3	861	92	9.7 %	0.0 %
SE	0	1,800	7,117	22,015	19,376	16,334	71	4,016	91	0	1,303	34.3	21.7	18,596	3,031	14.0 %	0.0 %
SI	654	589	688	5,598	175	1,182	0	133	625	0	162	82.5	35.2	6,020	743	11.0 %	0.0 %
SK	0	1,022	4,142	3,564	126	411	1,228	300	1,017	0	297	80.2	34.5	3,565	594	14.3 %	0.0 %
TR	23,891	15,976	5,920	52,500	18,574	7,755	20,536	2,300	1,400	0	3,299	37.1	18.1	76,412	8,660	10.2 %	0.0 %
UA	6,991	2,276	13,835	31,122	5,400	195	5,051	93	1,563	0	1,408	75.8	30.7	32,182	3,017	8.6 %	0.0 %
UK	559	22,276	6,848	70,223	42,422	1,914	0	17,413	5,033	0	2,914	46.8	23.9	58,279	16,168	21.7 %	0.0 %
	Scenario: Very high PV − 20 % battery																
	Capacity mix, MW											Baseload price, €/MWh	PV market value, €/MWh	PV production, MWh	PV curtailment, MWh	PV curtailment ratio, %	Battery utilization, %
	Coal and lignite	Natural gas and other fossil	Nuclear	PV	Wind	Run-of river	Hydro Storage	Other RES	Pumped storage	Battery	DSM						
AL	0	0	0	1,500	13	532	1,723	6	0	303	83	81.9	42.5	1,950	42	2.1 %	19.4 %
AT	0	4,262	0	36,000	6,124	5,897	3,161	947	6,678	8,425	699	75.6	37.6	38,434	3,714	8.8 %	16.1 %
BA	1,800	0	0	1,050	486	296	1,482	7	1,551	307	120	81.3	42.3	1,328	48	3.5 %	17.4 %
BE	0	3,989	0	31,200	7,595	106	0	880	1,307	7,759	990	74.1	34.6	29,434	3,551	10.8 %	15.5 %
BG	60	2,282	2,080	9,649	1,106	543	1,826	210	1,404	2,151	326	78.0	37.3	13,098	324	2.4 %	17.3 %
BY	0	2,403	2,388	927	65	46	0	136	0	199	384	72.9	61.7	958	0	0.0 %	1.4 %
CH	0	589	2,715	29,400	232	5,531	10,816	1,197	4,914	5,926	568	46.4	26.8	29,182	6,500	18.2 %	19.0 %
CZ	6,264	2,129	4,164	24,476	945	360	753	1,119	1,175	5,084	656	76.4	35.7	23,432	2,368	9.2 %	16.3 %
DE	24,537	26,297	0	288,419	82,405	3,841	1,429	8,972	6,442	74,165	5,608	74.6	34.4	220,477	21,997	9.1 %	14.6 %
DK	140	819	0	19,401	10,485	7	0	2,040	0	5,977	441	65.4	29.9	17,635	2,256	11.3 %	14.4 %
EE	395	281	0	1,245	1,254	4	0	241	0	500	97	72.8	60.1	1,301	0	0.0 %	20.3 %
ES	92	32,129	5,315	137,112	50,928	1,239	13,544	2,442	6,166	37,608	2,623	28.1	17.5	151,958	61,681	28.9 %	17.8 %
FI	1,804	2,506	4,622	4,494	6,295	3,225	0	2,509	0	2,158	908	39.0	28.3	4,190	102	2.4 %	8.3 %
FR	0	9,324	57,217	131,343	26,498	11,196	8,911	2,534	5,589	31,568	4,348	37.9	22.9	138,885	25,847	15.7 %	16.6 %
GR	660	6,496	0	22,413	6,546	352	2,673	344	1,379	5,792	581	78.6	34.6	27,930	2,485	8.2 %	17.5 %
HR	210	1,344	0	2,250	1,614	434	1,468	180	822	773	202	81.4	41.8	2,668	41	1.5 %	16.1 %
HU	0	3,195	2,026	19,362	369	39	28	767	0	3,946	551	80.9	39.9	23,325	566	2.4 %	16.0 %
IE	0	3,829	0	1,800	8,816	217	22	165	2,152	2,123	432	56.0	46.2	1,793	56	3.0 %	11.2 %
IT	5,190	50,724	0	156,000	13,766	10,507	4,441	4,035	8,409	33,953	3,274	76.9	30.8	181,531	38,415	17.5 %	17.7 %
KO	540	0	0	1,017	360	53	74	19	0	275	70	82.0	42.3	1,397	28	2.0 %	17.5 %
LT	0	655	0	3,750	1,905	133	5	152	900	1,131	122	73.1	60.9	3,707	0	0.0 %	14.8 %
LU	0	293	0	1,824	237	25	11	44	1,296	412	67	74.6	36.1	1,633	332	16.9 %	17.9 %
LV	6	1,244	0	326	428	1,689	0	201	0	151	78	72.8	60.6	332	0	0.0 %	38.6 %
MD	1,600	1,332	0	52	100	89	0	12	0	30	47	79.0	40.2	54	6	10.1 %	66.7 %
ME	225	0	0	95	225	355	381	0	0	64	37	82.0	41.7	115	7	6.0 %	44.5 %
MK	0	383	0	1,689	85	13	720	10	333	355	80	81.9	43.4	2,351	43	1.8 %	16.3 %
NL	274	10,263	515	81,791	13,824	38	0	687	0	19,123	1,291	73.6	32.8	64,216	15,585	19.5 %	15.2 %
NO	0	1,082	0	1,800	9,391	5,801	25,385	49	1,392	2,238	1,279	28.9	22.0	1,618	77	4.5 %	4.9 %
PL	19,956	5,308	0	15,342	17,043	453	493	2,506	2,519	6,477	1,829	96.2	85.2	15,859	0	0.0 %	7.9 %
PT	0	4,033	0	23,284	9,022	2,973	1,576	1,006	4,515	6,461	542	28.5	18.2	27,950	8,645	23.6 %	18.0 %
RO	330	3,353	2,813	15,162	5,026	2,870	3,467	382	1,258	4,038	698	79.1	40.3	19,466	63	0.3 %	16.0 %
RS	3,096	1,255	0	705	1,169	2,064	476	50	628	375	331	81.3	42.6	928	25	2.6 %	19.5 %
SE	0	1,800	7,117	22,015	19,376	16,334	71	4,016	91	8,278	1,303	34.2	23.4	20,973	654	3.0 %	7.6 %
SI	654	589	688	5,598	175	1,182	0	133	625	1,155	162	80.7	39.5	6,501	262	3.9 %	16.9 %

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	Capacity mix, MW											Baseload price, €/MWh	PV market value, €/MWh	PV production, MWh	PV curtailment, MWh	PV curtailment ratio, %	Battery utilization, %
	Coal and lignite	Natural gas and other fossil	Nuclear	PV	Wind	Run-of river	Hydro Storage	Other RES	Pumped storage	Battery	DSM						
	Scenario: Very high PV – 20 % battery																
SK	0	1,022	4,142	3,564	126	411	1,228	300	1,017	738	297	77.8	38.7	3,965	194	4.7 %	15.5 %
TR	23,891	15,976	5,920	52,500	18,574	7,755	20,536	2,300	1,400	14,215	3,299	34.8	18.8	83,766	1,306	1.5 %	17.0 %
UA	6,991	2,276	13,835	31,122	5,400	195	5,051	93	1,563	7,304	1,408	73.8	34.9	34,796	403	1.1 %	15.8 %
UK	559	22,276	6,848	70,223	42,422	1,914	0	17,413	5,033	22,529	2,914	44.8	27.6	68,835	5,612	7.5 %	13.7 %
	Scenario: Medium PV – 5 % battery (Optimal)																
	Capacity mix, MW											Baseload price, €/MWh	PV market value, €/MWh	PV production, MWh	PV curtailment, MWh	PV curtailment ratio, %	Battery utilization, %
	Coal and lignite	Natural gas and other fossil	Nuclear	PV	Wind	Run-of river	Hydro Storage	Other RES	Pumped storage	Battery	DSM						
AL	0	0	0	1,000	13	532	1,723	6	0	51	83	90.5	55.5	1,325	3	0.2 %	39.0 %
AT	0	4,262	0	24,000	6,124	5,897	3,161	947	6,678	1,506	699	85.6	46.9	26,727	1,371	4.9 %	17.2 %
BA	1,800	0	0	700	486	296	1,482	7	1,551	59	120	90.1	55.3	913	4	0.5 %	25.9 %
BE	0	3,989	0	20,800	7,595	106	0	880	1,307	1,420	990	94.5	42.2	20,834	1,156	5.3 %	17.8 %
BG	60	2,282	2,080	6,432	1,106	543	1,826	210	1,404	377	326	85.9	47.9	8,919	29	0.3 %	17.6 %
BY	0	2,403	2,388	618	65	46	0	136	0	34	384	84.2	73.4	639	0	0.0 %	0.3 %
CH	0	589	2,715	19,600	232	5,531	10,816	1,197	4,914	992	568	52.2	30.5	21,354	2,434	10.2 %	28.8 %
CZ	6,264	2,129	4,164	16,317	945	360	753	1,119	1,175	863	656	86.6	45.2	16,597	603	3.5 %	18.1 %
DE	24,537	26,297	0	192,279	82,405	3,841	1,429	8,972	6,442	13,734	5,608	85.0	43.6	156,630	5,020	3.1 %	16.8 %
DK	140	819	0	12,934	10,485	7	0	2,040	0	1,171	441	74.7	37.8	12,187	1,074	8.1 %	16.7 %
EE	395	281	0	830	1,254	4	0	241	0	104	97	81.1	71.7	867	0	0.0 %	21.7 %
ES	92	32,129	5,315	91,408	50,928	1,239	13,544	2,442	6,166	7,117	2,623	40.5	20.5	110,320	32,106	22.5 %	18.0 %
FI	1,804	2,506	4,622	2,996	6,295	3,225	0	2,509	0	465	908	42.8	32.5	2,771	91	3.2 %	8.3 %
FR	0	9,324	57,217	87,562	26,498	11,196	8,911	2,534	5,589	5,703	4,348	40.9	23.6	98,994	10,828	9.9 %	18.4 %
GR	660	6,496	0	14,942	6,546	352	2,673	344	1,379	1,074	581	85.2	43.9	19,755	522	2.6 %	18.0 %
HR	210	1,344	0	1,500	1,614	434	1,468	180	822	156	202	90.3	54.9	1,802	4	0.2 %	16.8 %
HU	0	3,195	2,026	12,908	369	39	28	767	0	664	551	89.7	52.8	15,893	35	0.2 %	16.6 %
IE	0	3,829	0	1,200	8,816	217	22	165	2,152	501	432	59.4	50.3	1,185	48	3.9 %	17.3 %
IT	5,190	50,724	0	104,000	13,766	10,507	4,441	4,035	8,409	5,888	3,274	81.9	38.0	133,344	13,287	9.1 %	17.8 %
KO	540	0	0	678	360	53	74	19	0	52	70	90.5	55.5	949	1	0.1 %	44.6 %
LT	0	655	0	2,500	1,905	133	5	152	900	220	122	81.4	72.4	2,471	0	0.0 %	16.3 %
LU	0	293	0	1,216	237	25	11	44	1,296	73	67	85.0	44.9	1,137	173	13.2 %	19.1 %
LV	6	1,244	0	218	428	1,689	0	201	0	32	78	81.1	72.1	221	0	0.0 %	20.7 %
MD	1,600	1,332	0	35	100	89	0	12	0	7	47	86.7	51.8	40	0	0.8 %	51.1 %
ME	225	0	0	63	225	355	381	0	0	14	37	90.5	54.8	81	1	0.8 %	76.9 %
MK	0	383	0	1,126	85	13	720	10	333	61	80	90.5	56.4	1,593	3	0.2 %	17.4 %
NL	274	10,263	515	54,528	13,824	38	0	687	0	3,418	1,291	94.3	41.2	45,623	7,578	14.2 %	17.3 %
NO	0	1,082	0	1,200	9,391	5,801	25,385	49	1,392	530	1,279	31.9	24.9	1,093	37	3.3 %	6.3 %
PL	19,956	5,308	0	10,228	17,043	453	493	2,506	2,519	1,364	1,829	100.2	88.2	10,572	0	0.0 %	13.3 %
PT	0	4,033	0	15,523	9,022	2,973	1,576	1,006	4,515	1,227	542	41.9	22.9	20,310	4,087	16.8 %	18.4 %
RO	330	3,353	2,813	10,108	5,026	2,870	3,467	382	1,258	757	698	86.8	51.8	13,019	0	0.0 %	16.4 %
RS	3,096	1,255	0	470	1,169	2,064	476	50	628	82	331	90.1	55.6	634	1	0.1 %	29.0 %
SE	0	1,800	7,117	14,677	19,376	16,334	71	4,016	91	1,703	1,303	37.6	27.0	13,921	497	3.4 %	7.9 %
SI	654	589	688	3,732	175	1,182	0	133	625	195	162	89.6	52.5	4,489	19	0.4 %	17.4 %
SK	0	1,022	4,142	2,376	126	411	1,228	300	1,017	125	297	87.8	51.3	2,755	17	0.6 %	16.8 %
TR	23,891	15,976	5,920	35,000	18,574	7,755	20,536	2,300	1,400	2,679	3,299	39.3	24.5	56,656	59	0.1 %	16.0 %
UA	6,991	2,276	13,835	20,748	5,400	195	5,051	93	1,563	1,307	1,408	82.4	46.1	23,464	2	0.0 %	19.8 %
UK	559	22,276	6,848	46,815	42,422	1,914	0	17,413	5,033	4,462	2,914	50.0	30.6	47,479	2,153	4.3 %	16.8 %

Data availability

Data will be made available on request.

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