An Analysis of EU Power System Flexibility: Storage Capacity Needs under Increasing Variable Renewable Energy Sources (VRES) Penetration

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ABSTRACT

The increasing penetration of variable renewable energy sources in the energy mix plays a key role in the energy transition but it also poses serious challenges in terms of grid scheduling, regulation, management, and resilience. To cope with the non-programmable nature of renewables, increased generation reserves, ramp rates and curtailments are required to meet the electricity demand with an increasingly uncertain supply and to provide flexibility services to the grid. To avoid excessive operational costs and mounting inefficiencies, the grid calls for higher flexibility requirements from the electricity system. Currently, this can be provided only by conventional generators (such as thermo-electric or hydro-electric), by demand shifting (mainly by industrial loads) or by energy storage systems, whose current limited adoption is still insufficient for such objective. The definition of such flexibility requirements is still an open topic in the literature, with few analyses available targeting the problem in a quantitative fashion, especially when future energy scenarios are considered.
For these reasons, this study provides insights into the historical trends of flexibility parameters in three representative EU members (Italy, Germany and Hungary). These parameters are discussed separately for each country and compared among countries through a novel visualization mode which traces their temporal evolution and seasonal patterns and allows comparison between electrical grids with varying power levels.
Furthermore, the study anticipates diverse future scenarios for the Italian power system, considering increased variable renewables penetration. Each scenario is analyzed for renewable generation curtailments and seasonal variations in renewable energy supply. The assessment of different storage needs in terms of capacity and duration provides a quantitative foundation for addressing the evolving flexibility requirements in the face of future energy scenarios. Particularly, future scenarios for Italy highlight the potential need for short-term energy storage systems, such as batteries, with a capacity between 10 and 110 TWh/year to avoid renewable curtailment levels ranging from 5% to 40%. Alternatively, by expanding the potential for use to sectors other than electricity generation, the same curtailment levels could be used to generate green hydrogen, between 0.2-1.9 million tons per year. The results underscore the importance of balanced increases in wind and solar capacities to optimize flexibility and reduce seasonal storage demands, showcasing the study's relevance in shaping informed energy transition strategies.

1 INTRODUCTION

Addressing the growing integration of Variable Renewable Energy Sources (VRES) in the power grids represents a significant goal of the energy transition process. In fact, the non-programmable nature of VRES production poses new challenges to the stability and security of power grids. In order to address these challenges, future power systems must exhibit higher flexibility (Migliari et al., 2023) for effective energy balancing of the grid. In this context, flexibility is described as the ability of a power system to

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manage the variability and uncertainty of demand and supply at different time scales, avoiding curtailment of VRES (Hussain et al. 2023; Lund et al. 2015; IRENA 2018). The flexibility of a power grid is usually measured by means of three parameters (IRENA, 2018). Two parameters are referred to the net load, which is given by the difference between the gross load and the electricity generated from VRES (wind and solar), while the third is referred to the uncertainty of VRES production. More in detail, the three parameters are: 1) the Ramp rate ($R^{\pm}$), representing the rate of change of the net load; 2) the daily Ramping Range (RR_d), indicating the difference between the maximum and minimum net load within a day; and 3) the uncertainty due to forecast errors. The increasing penetration of VRES in power grids significantly impacts these factors, causing the risk of non-manageable uncertainty and imbalances between generation and demand. Flexibility must be achieved by improving transmission grids, implementing Energy Storage Systems (ESS) (Petrollese et al., 2016), and managing production and demand, both on the supply and the demand sides (Lund et al., 2015). Currently, flexibility is a service almost completely provided by the supply side of electrical grids by means of conventional generators, gas turbines, hydropower plants, pumped hydro storage and, if necessary, VRES generation curtailment (IRENA, 2018)). On the other hand, flexibility measures predominantly employed on the demand-side of electrical grids are extreme (Migliari et al., 2024) and significantly detrimental to the service, involving load shedding and load curtailment. One of the main challenges in increasing VRES penetration is to provide such flexibility services, to the greatest extent possible, without resorting to curtailment and at different time scales, spanning from sub-seconds (for addressing inertia imbalances), to hours, and even years (Helman et al. 2020; IRENA 2018; Hussain et al. 2023). According to (Helman et al., 2020), the very short duration needs (online in a few milliseconds to 5 minutes), such as primary frequency response and frequency regulation, can be addressed by means of technologies such as flywheels, supercapacitors, and demand-side management via load shifting. Short duration needs (online in 5 minutes to 1 hour) concern spinning and non-spinning reserves (5 min), contingency reserve (1 hour) and black start (start-ups or failure recovery). While spinning and non-spinning reserve services are typically provided by means of gas turbines, black start services can be provided by means of suitable ESS such as Pumped Hydro Energy Storage (PHES) plants, Battery Energy Storage Systems (BESS) and Compressed Air Energy Storage (CAES) plants. Intermediate duration services (between 1 hour and 3 days) include load following, used to balance supply with demand, load levelling, which consists of storing energy during off-peak demand periods for a subsequent release during peak demand periods, unit commitment with ESS to cope with uncertainties in the scheduling of the power supply, and energy arbitrage which can increase profitability of ESS. Lastly, long duration needs (seasonal) consist of seasonal shifting and seasonal energy arbitrage and require very high ESS capacities.

Given the undeniable priority of energy transition, in recent years there has been a growth in research focused on flexibility in power grids. In this regard, (Yasmin et al., 2024) analyzed recent research trends and conducted a survey focusing on ESS coupled with onsite generation integrated into demand response mechanisms to enhance flexibility. (Alizadeh et al., 2016) conducted a literature review to identify the effects of flexibility on the power system. To address uncertainties from VRES power systems they suggested using optimization methods for scheduling market operations. Additionally, better identification of ramp behavior can help balance production and demand. (Impram et al., 2020) defined the effects of VRES on power system stability and proposed different methods to increase flexibility, such as demand-side management strategies, using fossil-fuelled power plants to provide power at high ramping times, optimal scheduling of combined heat and power plants operations, improving the transmission network and, as a final option, curtailment of excess production. (Shah et al., 2015) investigated the challenges of high PV generation in power system stability. They concluded that all different aspects of grid stability should be considered in order to develop large-scale PV plants while ensuring secure and stable operation of the power system. They finally suggested that optimal operational scheduling and spinning reserve should be implemented to address stability issues. (Alexopoulos et al., 2021) categorized and discussed different flexibility measures, emphasizing that all flexibility issues could not be addressed with a single measure. Additionally, they studied the Greek power system, proposing the introduction of new market strategies to incorporate ESS. (Hussain et al., 2023) analyzed in detail the different aspects of flexibility, highlighting the significance of establishing standardized flexibility parameters and proposed the adoption of specific remuneration structures for flexibility services. (Headley and Copp, 2020) studied the introduction of ESS in grids with high VRES

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penetrations considering the limitations in the ramp rate. Specifically, they applied a mixed integer linear programming optimization method to the California case, determining the minimal capacity and nominal power of the storage system and employing a curtailment strategy to balance production and demand.

Within this framework, the present study, starting from an in-depth analysis of the grid flexibility characteristics for three European countries characterized by very different energy mixes (Italy, Germany, and Hungary), aims to assess the changes in flexibility parameters for Italy as VRES penetration increases, considering various levels and distribution between Wind Turbines (WT) and Photovoltaic (PV) systems. For each scenario, the study assesses the amount of VRES energy at risk of curtailment and evaluates both the potential need for either storing this energy or converting it into green hydrogen.

The novelties of this study can be found, firstly, in a new representation of the energy mix, focused on programmable and not-programmable sources. Secondly, the study highlights the influence of the aforementioned energy mix on the yearly average duck curves, differentiating their components between WT and PV, analyzing their temporal evolution, and comparing them across the considered countries. In addition, the study proposes an evolution of the ramping range flexibility indicator in order to enable a comparison between electrical grids with varying power levels. Moreover, the study provides a visualization of flexibility parameters, tracing their temporal evolution, seasonal patterns, and comparisons across different countries. Finally, the research evaluates the storage needs in terms of energy and duration with varying percentages of VRES increment, aiming to not worsen the current flexibility levels and to reduce generation curtailment.

2 METHODS

This section outlines the methods employed to assess the historical evolution, the current levels, and the future scenarios of flexibility in the considered power systems.

The input data of hourly load and generation used in the present study have been retrieved by (ENTSO-E, 2024) and have been used to calculate annual and seasonal energy mix as well as the hourly average annual net load curve, also known as "duck curve" (CAISO, 2024) utilizing MATLAB version R2024a (The MathWorks Inc., n.d.). In this work, "gross load" refers to the total electricity demand and consequently production excluding the balance of exchanges on interconnections between neighboring zones and the power absorbed by ESS, while "net load" refers to the difference between the gross load and the electricity generated from VRES (wind and solar). The flexibility levels have been assessed by using the metrics (ramp rate and ramping range) proposed by (IRENA, 2018) through a statistical analysis.

Specifically, the Ramp rate ($R^{\pm}$) of the net load, representing the maximum hourly increase (+) or decrease (-) of net load within the considered period, indicates both the demand slope required by the power generation systems, excluding VRES, and the ability of these non-VRES systems to fulfill this demand. High penetration levels of VRES necessitate a significant availability of programmable power sources or ESS ready to compensate for sudden or anticipated reductions in generation capacity, leading to steep ramp rates. These ramps may be upward (R^{+}), necessitating programmable sources to offset a reduction in VRES output (such as during the evening), or downward (R^{-}), requiring programmable generation plants to reduce their output or shut down in response to an increase in VRES generation.

The Ramping Range ($\mathrm{RR_d}$) is a further index analyzed, representing the span between the highest and lowest net load within a day. To facilitate effective comparison across countries with varying electric loads, this study normalizes the RR_d using the highest net load recorded throughout the year in each country ($NL_{max,y}$), thus obtaining a relative ramping range ($RR_d/NL_{max,y}$), a new indicator that can be used instead of using absolute figures. The normalization factor has been chosen because it indicates the modulation capacity of the dispatchable non-VRES systems. In the discussion, "average relative ramping range" refers to the mean value of the ramping range over the considered period, normalized by the maximum net load occurred throughout the year.

In the second part of the present study, a forward-looking analysis is conducted to anticipate the impact of higher VRES penetration on the power systems, with a particular focus on Italy. This analysis considers the need for increased RES production to meet future energy demands and decarbonization

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goals. For this reason, under the assumption of maintaining the same level of consumption, the increased energy productions from RES are considered to partially replace the current energy production from programmable sources (mainly using fossil fuels). To simulate scenarios of heightened RES integration, the current capacities for PV and WT systems have been adjusted upwards through the application of various incremental factors.
Maximum ramp rates and ramping range are then calculated by means of a statistical analysis and potential energy curtailment is assessed assuming that the current level of flexibility resources remains constant. In particular, the energy curtailed is calculated as the sum of energy potentially available every hour from VRES resources that if supplied to the system would exceed the ramping limits of the programmable sources. The battery storage capacity required to store such energy curtailment has been then calculated considering the state-of-the-art roundtrip efficiency of the technology (AlShafi and Bicer, 2021), while state-of-the-art efficiencies for different electrolysis technologies (Flis, 2023) have been used to compute the amount of hydrogen that could be generated by using the energy otherwise curtailed.
The objective of this study is to provide a preliminary and high-level indication of the potential flexibility requirements of the grid based on variable penetration levels of VRES. Potential sources of additional flexibility such as demand side management, international connections, unit dispatchment and load shifting of industrial and residential aggregates are not considered. Given that, the outcomes of the research are to be intended as conservative and more in-depth future studies will be carried out.

3 RESULTS AND DISCUSSION

The current chapter is structured as follows: Section 3.1 presents the evolution of flexibility parameters over the last 8 years for three representative EU countries, along with the seasonal variability for the year 2023. Subsequently, Section 3.2 reports, for various power mix evolution scenarios of Italy, the flexibility parameters as well as the potential generation curtailment and storage requirements to mitigate it. The latter are then discussed in relation to annual and seasonal needs, considering two distinct storage types: BESS and hydrogen.

3.1 Analysis of historical and seasonal trends

The historical and seasonal analysis of the present study has been focused on three EU Member States, Italy (IT), Germany (DE) and Hungary (HU), given their different energy mix, as shown in Figure 1(a-b). DE is characterized by a strong prevalence of WT, HU by a strong (almost absolute) prevalence of PV, and IT represents an intermediate condition. The diagrams highlight the share of PV, WT and Hydro Run-of-River ($H_{R\text{-}o\text{-}R}$) electricity generated in the years 2015 and 2023. Programmable sources ("Progr." in Figure 1(a-b)), including thermoelectric generation, programmable hydro and biomass are aggregated and shown in blue.
In 2015 (Figure 1(a)), IT relied heavily on programmable sources, accounting for 76.8% of its energy mix, with $H_{R\text{-}o\text{-}R}$ contributing 11.8%, WT 5.0%, and PV 6.4%. DE also depended largely on programmable sources at 74.0% but had a significant share from WT (16.0%) and PV (7.2%), with $H_{R\text{-}o\text{-}R}$ at 2.7%. HU showed a vast reliance on programmable sources at 98.2%, with negligible contributions from the other sources.
By 2023 (Figure 1(b)), notable changes occurred. In IT, the share of programmable sources decreased to 71.8%, while $H_{R\text{-}o\text{-}R}$ remained almost stable at 11.2%. Contributions from WT and PV increased to 8.2% and 8.7%, respectively. DE saw a substantial shift, with programmable sources dropping to 52.5%, while WT surged to 32.0% and PV to 12.5%, indicating a significant shift towards VRES. Even in this case, $H_{R\text{-}o\text{-}R}$ remained almost unchanged at 3%. HU, although still heavily reliant on programmable sources (87.8%), showed increased adoption of PV (10.5%) as a substitution for programmable sources, and a minor increase in WT (1.5%) systems.

(a) **- 2015** (b) - **2023**

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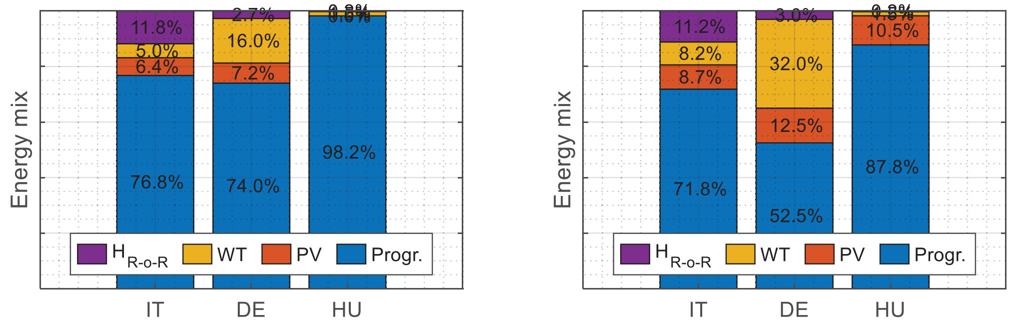

Figure 1: Energy mix in Italy (IT), Germany (DE), and Hungary (HU) in 2015(a) and 2023(b)
Progr.=Programmable sources; WT=Wind Turbines; $H_{R\text{-}o\text{-}R}$*= Hydro Run-of-River; PV=Photovoltaic.*

Figure 2(a-f) shows the hourly average duck curves (in blue) and load profiles calculated over the years 2015 (Figure 2(a-c)) and 2023 (Figure 2(d-f)) for the three different countries. All three States exhibit a general decrease in the gross load and a deepening of the minimum net load, due to the significant share of PV production on their VRES mix. Specifically, the net load share on gross load at 1 pm in IT decreased from approximately 77% (28.3 GW over 36.8 GW) in 2015 (Figure 2(a)) to 68% (23.4 GW over 34.5 GW) in 2023 (Figure 2(d)); in Germany, it decreased from 67% (43.9 GW over 65.4 GW) in 2015 (Figure 2(b)) to 41% (24.2 GW over 59.4 GW) in 2023 (Figure 2(e)) and in Hungary, it decreased from nearly 100% in 2015 (Figure 2(c)) to 64% (3.1 GW over 4.8 GW) in 2023 (Figure 2(f)). Differently from IT and DE, HU exhibits a general increase of the gross load in the evening (around 8 pm) from 2015 (Figure 2(c)) to 2023 (Figure 2(f)). Moreover, the increase of VRES in HU results in a wide difference between the net and gross load curves in 2023 with respect to 2015, when they were practically overlayed. All the 2023 curves (Figure 2(d-f)) are characterized by the same trend of the net load: a morning peak around 9 am, a midday valley around 1 pm, and an evening peak around 8 pm, more or less pronounced.

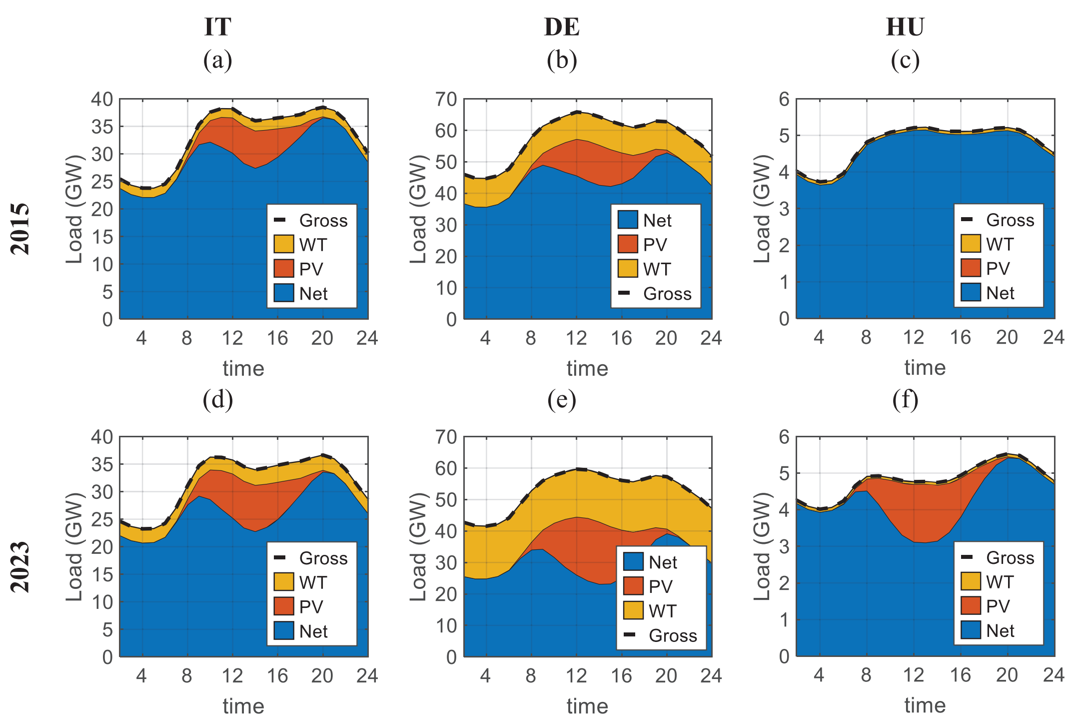

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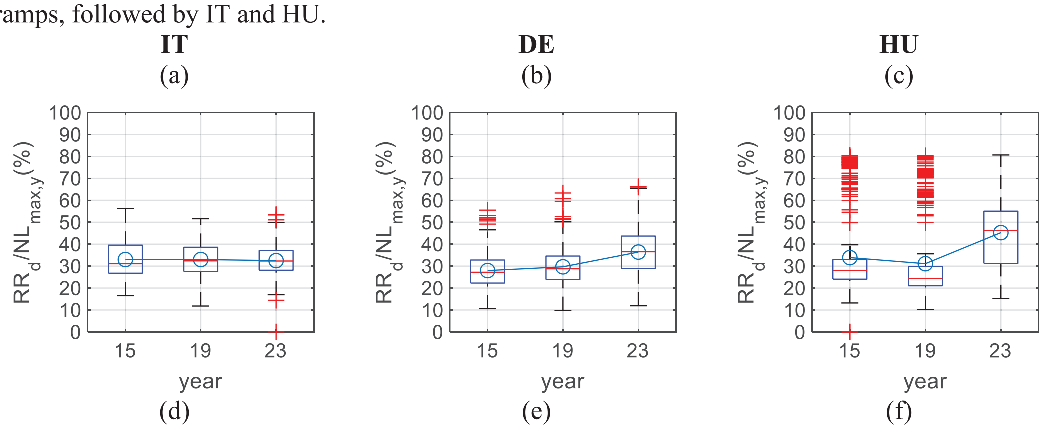
Figure 2: Yearly average duck curves and load profiles. In Italy (IT) in 2015(a) and 2023(d), in Germany (DE) in 2015(b) and 2023(e), and in Hungary (HU) in 2015(c) and 2023(f).
Gross=Gross load; WT=Wind Turbines generation; PV=Photovoltaic generation.

Figure 3(a-c) shows that the average values[1] of $RR_d/NL_{max,y}$ (relative ramping range) for the years 2015, 2019 and 2023 are consistently below 50% for all the three considered countries. For IT, Figure 3(a) shows a progressive reduction in both variability and maximum values in the relative ramping range, whose average value, however, remains above 30%. In DE (Figure 3(b)), on the contrary, a clear opposite trend can be observed: in 2023, the average value of the relative ramping range increased to over 35%, along with increased variability and higher maximum values, reaching 65%. HU (Figure 3(c)) shows a significant change in the values of the relative ramping range between 2015 and 2023, caused by the increase in PV not balanced by an increase in WT. The $RR_d/NL_{max,y}$ values in 2023 range between 15% and 80%, with an average around 45%. Clearly, the most critical situation for grid flexibility is represented by HU: high values of the relative ramping range indeed result in higher modulation of non-VRES units, which brings drawbacks to operational efficiency and decreases the reserve margins. On the other hand, the IT current situation is the most favorable and it also shows a downward trend (improvement) compared to both previous years and to the other countries. With regard to ramp rates R^+ and R^- (Figure 3(d-f)), the DE averages (Figure 3(e)) are approximately twice those of IT (Figure 3(d)), which, in turn, are approximately four-five times the HU averages (Figure 3(f)). IT maximum values do not exceed 8 GW/h (Figure 3(d)), whereas DE values reach 14 GW/h (Figure 3(e)). Networks with low ramp rates are preferable because they can be managed by non-VRES units with slower operating dynamics, whereas networks with high ramp rates require faster responses, such as those provided by gas turbines and BESS, effectively limiting the range of power generation systems' utilization. These differences in ramp rates are to be interpreted in relation to the load levels of the three states. Therefore, it is clear that DE, which is characterized by the highest loads, presents the steepest ramps, followed by IT and HU.



[1] Calculated as the annual average of the daily ramping range normalized by the maximum net load throughout the year and identified by the blue circles.

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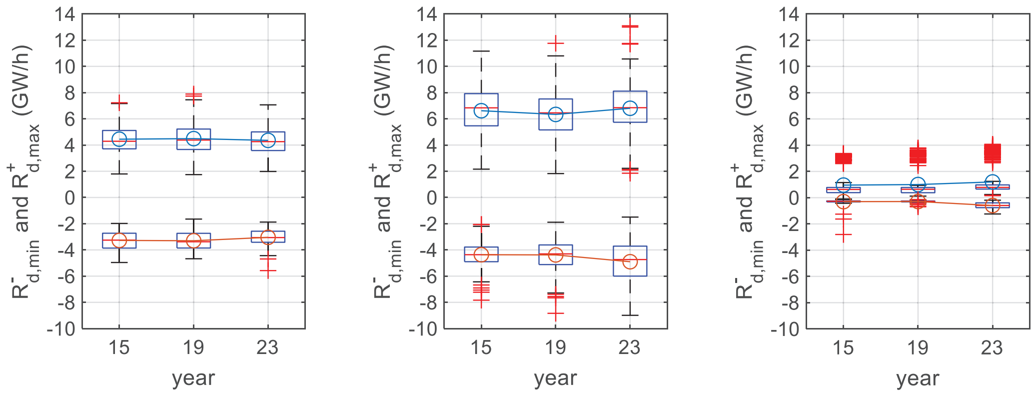
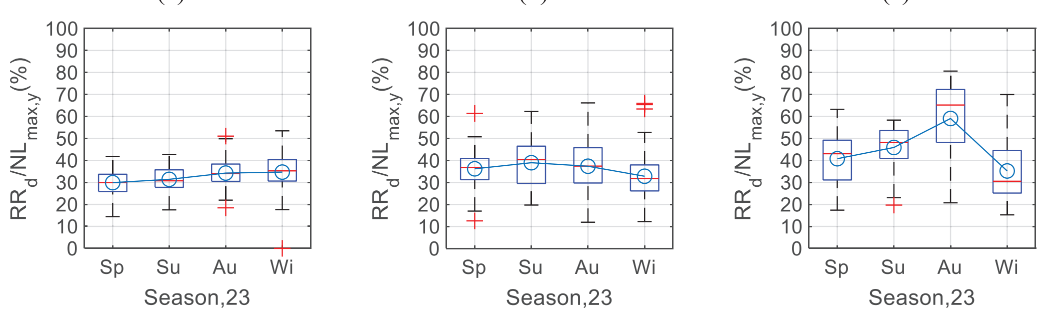


Figure 3. Relative ramping range ($RR_d/NL_{max,y}$) and ramp rates ($R^-_{d,min}$, $R^+_{d,max}$) in Italy (IT)(a,d), Germany (DE)(b,e), and Hungary (HU)(c,f) in 2015, 2019 and 2023.
RR_d=Daily ramping range; $NL_{max,y}$=maximum yearly net load; $R^-_{d,min}$= minimum daily ramp rate; $R^+_{d,max}$=maximum daily ramp rate.

The seasonal trend of the flexibility parameters, reported in the following Figure 4, is different for the three considered countries. Regarding the relative ramping range for IT (Figure 4(a)), a slight increase in average values is observed during cold seasons, when the minimum net load (which occurs in the morning rather than midday) is deeper, and the maximum remains consistent with values of other seasons. Statistical variability (lower-upper quartiles) in IT remains relatively constant across the four seasons. For DE (Figure 4(b)), a slight increase in average values, variability and whiskers extension is observed in summer and autumn, motivated by the low value of the daily average minimum net load, which occurs in the middle of the day in summer and in the morning during autumn (when PV production is lower). In HU (Figure 4(c)), an increase in both variability and average values is observed during autumn, with the latter likely attributable to the rise in evening peaks, presumably due to electrical loads associated with heat pump heating, not possible in winter due to extreme temperatures. Additionally, Figure 4(d-f) display $R^-_{d,min}$ and $R^+_{d,max}$ across different seasons in 2023. In IT (Figure 4(d)), both $R^-_{d,min}$ and $R^+_{d,max}$ average values increase significantly in their absolute values in the cold seasons (Au and Wi) compared to the warm seasons (Sp and Su). In fact, the reduction in PV generation and increased heating demand in the cold seasons necessitate greater ramping flexibility from non-VRES generators. Contrary to IT, the absolute values of the ramp rates decrease in the cold seasons in DE (Figure 4(e)): the higher WT capacity in Germany results in more stable and predictable WT energy during the cold seasons, reducing ramping needs. In HU (Figure 4(f)), average ramp rate values are relatively stable. In fact, absolute values of $R^-_{d,min}$ and $R^+_{d,max}$ for HU are lower compared to the other States. However, it should be noted that HU is characterized by a peak demand almost 10 times lower than DE and about 7 times lower than IT.

IT **DE** **HU**
(a) (b) (c)



(d) (e) (f)

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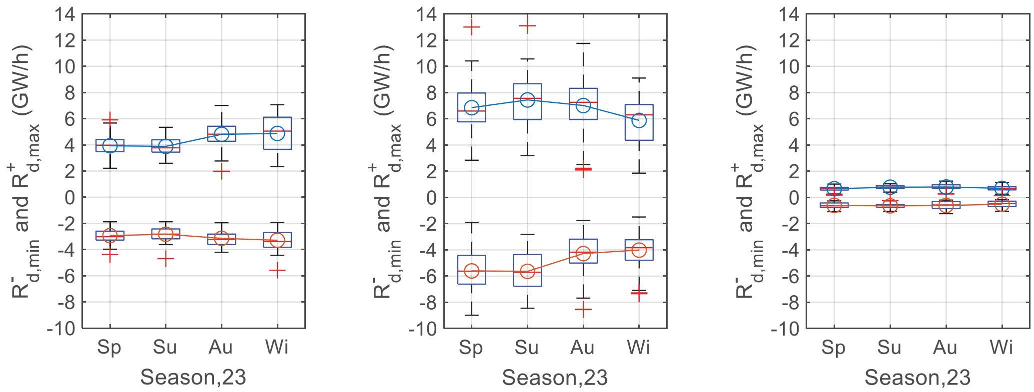

Figure 4. Relative ramping range ($RR_d/NL_{max,y}$) and ramp rates ($R^-_{d,min}$, $R^+_{d,max}$) in Italy (IT)(a,d), Germany (DE)(b,e), and Hungary (HU)(c,f), seasons 2023.
RR_d=Daily ramping range; $NL_{max,y}$=maximum yearly net load; $R^-_{d,min}$= minimum daily ramp rate; $R^+_{d,max}$=maximum daily ramp rate; Sp=Spring; Su=Summer; Au=Autumn; Wi=Winter.

3.2 Analysis of future scenarios

Considering that Italy shows intermediate conditions of duck curves, relative ramping ranges and ramp rates among the three analysed countries, it has been chosen for the analysis of future scenarios of increasing VRES penetration. Given that, to assess the impact of increasing VRES penetration on the Italian power system flexibility parameters, three possible scenarios (Sc.1, Sc.2, Sc.3) have been considered, each of them in accordance with the IRENA recommendations of tripling the current RES capacity by 2030 (IRENA, 2023), also confirmed during the last COP28. Installed capacities of PV and WT systems in Italy at the end of 2023 were 30.28 GW and 12.34 GW, respectively, for a total VRES installed capacity of 42.62 GW. Speculatively, with respect to IRENA recommendations, it has been assumed to achieve the entire tripling of RES capacity (85.28 GW of new capacity in addition to the current 42.62 GW) by means of VRES.
The three considered scenarios are reported in Table 1: Sc.1 contemplates an imbalanced distribution of new VRES capacity in favour of PV systems (2/3 of the total VRES increment). Sc.2 considers instead a balanced distribution of the new capacity between WT and PV systems (1/2 of the total VRES increment each), while Sc.3 considers an imbalanced growth in favour of WT systems (2/3 of the total VRES increment).

Table 1: Scenarios of increased VRES penetration.

	Sc.1	**Sc.2**	**Sc.3**
Total VRES increment (GW)	85.28	85.28	85.28
New PV capacity on total VRES increment	2/3	1/2	1/3
New WT capacity on total VRES increment	1/3	1/2	2/3
New PV capacity (GW)	56.85	42.64	28.43
New WT capacity (GW)	28.43	42.64	56.85
Total PV capacity (GW)	87.13	72.92	58.71
Total WT capacity (GW)	40.77	54.98	69.19
Total VRES capacity (GW)	127.9	127.9	127.9
PV incremental factor on 2023 PV capacity	2.9	2.4	1.9
WT incremental factor on 2023 WT capacity	3.3	4.5	5.6

The seasonal energy mixes for Sc.1, Sc.2 and Sc.3 are shown in Figure 5(a-c). The hydro run-of-river ($H_{R\text{-}O\text{-}R}$) component is included in the blue category. In all scenarios (Figure 5(a-c)) the PV energy production is predominant in summer and spring while the share of energy generated by WT is higher

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in winter and autumn, reaching for Sc.3 up to 53% of the overall supply (Figure 5(c)). With reference to Sc.1(Figure 5(a)), it is interesting to note that the energy generated by PV systems in spring and summer (31-32%) is almost equal to the energy generated by WT systems in autumn and winter (29-33%). This allows to flatten the seasonal energy production imbalance and to reduce the need for long-term ESS, although at the expense of increasing intra-day storage needs. Another interesting point of view on different flexibility features is given by the average annual daily duck and load curves shown in Figure 5(d-f): the scenario with the highest share of WT system capacity (Sc.3 - (Figure 5(f))) allows to reduce the imbalance of energy production between day and night as well as to limit the steep ramps observed in the other two cases (Figure 5(d) and Figure 5(e)), caused by the higher penetration of PV that generates electricity mainly in the central part of the day. Sc.3 also allows to achieve slightly lower relative ramping ranges along the four seasons, assuming values from 20% to 55% (Figure 5(n)).

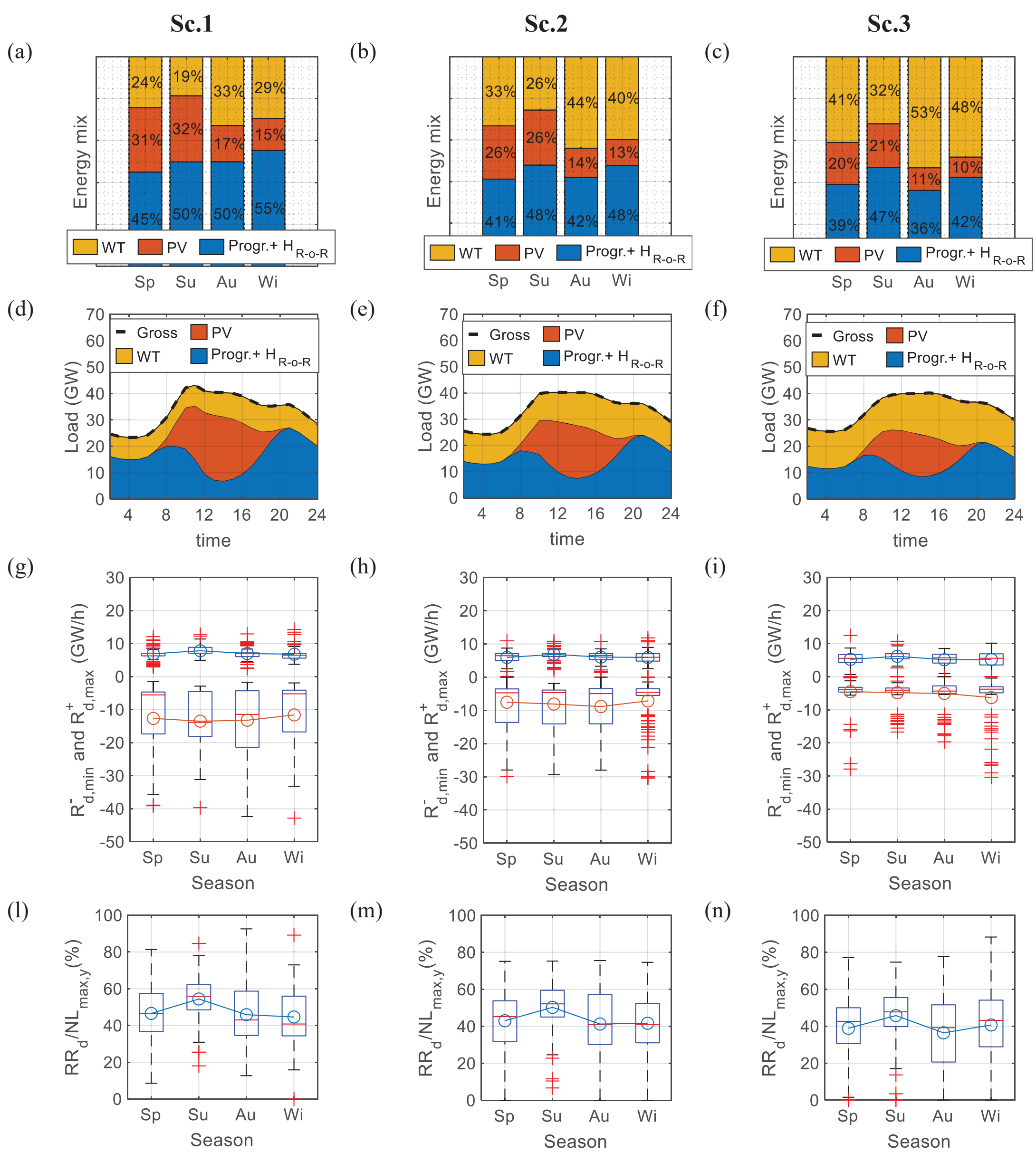

Figure 5: Seasonal energy mix (a-c), average annual daily duck curve (d-f), ramp rates (g-i) and relative ramping range (l-n) in Italy (IT) considering Sc.1, Sc.2 and Sc.3.

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WT=Wind Turbines; PV=Photovoltaic; Progr.+ $H_{R\text{-}o\text{-}R}$= Programmable sources and Hydro Run-of-River; Gross=Gross load.

Substantial increases in VRES penetration, as those hypothesized in the three scenarios or greater, can result in significant curtailment levels if not associated with an increase in ESS capacity or programmable power generation plants. For this reason, Figure 6(a) shows the share of VRES energy that would be curtailed on total producible for WT and PV incremental factors within the range 1-6 and for the three abovementioned scenarios Sc.1, Sc.2 and Sc.3 by means of a contour plot. In general, it is interesting to note that the VRES curtailment is more sensitive to an increase of the PV installed capacity rather than WT: increasing WT capacity even by a factor of 4-4.5, while keeping below 2 the PV incremental factor, leads only to a yearly energy curtailment of 10% (Figure 6(a)). However, on an annual basis and for the maximum values of the considered range of VRES incremental factors (WT incremental factor = 6; PV incremental factor = 6), Figure 6(a) shows that the highest amount of curtailed energy on total producible is around 40%. This suggests that in case of a rapid expansion of VRES capacity, the programmable resources or ESS which supply flexibility services to the system must increase as well. For this reason, Figure 6(b) reports the ESS capacity required to store the VRES energy otherwise curtailed, assuming an average round-trip efficiency of 90%, typical of BESS (AlShafi and Bicer, 2021): as it can be seen in Figure 6(b), up to 110 TWh of capacity could be required if WT and PV systems were implemented at rapid pace (WT incremental factor = 6; PV incremental factor = 6). With reference to the three considered scenarios, to avoid curtailment levels of 12% (Sc.1), 13% (Sc.2), and 16% (Sc.3), a BESS storage capacity of, respectively, 17 TWh, 19 TWh, and 25 TWh, is going be necessary.

An alternative viable option for avoiding VRES curtailment (Migliari et al., 2024) could involve producing hydrogen by means of electrolysis processes. The latter can then be used to substitute fossil fuels in various sectors, including industrial heating, heavy transportation, and chemicals. For this assessment, a specific energy consumption of 47 kWh/kg of H_2 has been considered, representing an average value among specific energy consumptions reported by Flis (Flis, 2023) for conventional technologies such as Proton Exchange Membrane (PEM), Anion Exchange Membrane (AEM) and Solid Oxide Electrolyzer Cell (SOEC). The potential annual hydrogen yield achievable through electrolysis processes, powered by the abovementioned unbalanced VRES generation, is included in the range 0.3-0.5 million tons for the three scenarios, as shown in the following Figure 6(c).

(a) (b) (c)

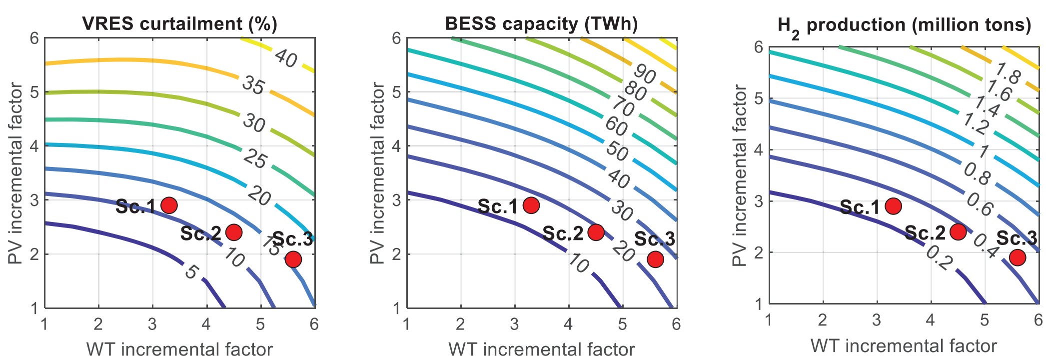

Figure 6: VRES energy curtailment on total producible (a), required BESS capacity for storing VRES curtailment (b) and potential annual hydrogen generation employing electrolyzers powered by VRES energy curtailment (c) at varying VRES penetration with different incremental factors (*WT=Wind Turbines; PV=Photovoltaic*).

4 CONCLUSIONS

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An analysis of the power system flexibility of three EU countries, Germany, Hungary and Italy, has been carried out, aimed to provide a representation of flexibility parameters and to evaluate storage capacity needs for Italy in order to avoid curtailment, under increasing VRES penetration scenarios.
Historical analyses have revealed a deteriorating trend in flexibility parameters both in Germany and Hungary. Conversely, Italy shows an improvement in flexibility parameters. In all countries, it is revealed a deepening trend of the duck curve belly, quantified through the new indicator of the relative ramping range, whose average value is between 30-40% of the maximum annual net load for Italy and Germany and between 35-60% for Hungary.
Future scenario analyses for Italy, which consider WT and PV incremental factors up to 6 times current levels, have allowed for the estimation of the required storage capacity. To avoid VRES curtailment levels ranging from 5% to 40% as well as seasonal imbalances from 5 to 40 TWh, a BESS with a capacity between 10 and 110 TWh/year will be necessary. Alternatively, the same VRES generation curtailments could be avoided powering green hydrogen electrolyzers, able to generate a hydrogen production within the range 0.2-1.9 million tons per year. Furthermore, the results have allowed estimating that an unbalanced distribution of new VRES capacity in favor of photovoltaic systems would pose the greatest flexibility challenges to the grid, while a balanced distribution of capacity in wind turbines and photovoltaic systems would significantly reduce the need for seasonal storage. In fact, wind production would be predominant in autumn and winter, and photovoltaic production in spring and summer. An unbalanced increase of new capacity in favor of wind turbine systems, on the other hand, would flatten the day-night differences, as the higher nighttime wind production would offset the higher daytime photovoltaic production.

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