Ancillary Services via Flexible Photovoltaic/Wind Systems and "Implicit" Storage to Balance Demand and Supply

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Achieving the European Union renewable energy source penetration 2030 targets requires an increase in flexible resources to compensate for the variability/intermittency of solar and wind generation to ensure system safety and balancing. Herein, two readily deployable flexibility solutions to balance demand/supply as an alternative to building additional thermoelectric reserves are proposed. How the transmission system OPERATOR can use the ancillary services provided by a flexible photovoltaic (PV) fleet (solar regulation) or PV/wind fleet (variable renewable energy (VRE) regulation) together with a suitable underforecast and proactive curtailment of variable renewable generation (aka, implicit storage) to reduce current and future Italian imbalances is shown. How these flexibility solutions can become even more effective when combined with a strengthening of the transmission grid is shown. The imbalance reduction achievable by 2030 through solar/VRE regulation strategies would be of the order of 20–50% with zonal balancing and 27–80% with nationwide balancing is found. Imbalance costs would remain comparable with the business-as-usual (thermal generation) costs. A proactive curtailment of 5–17% of the total VRE generation is the environmental cost of stabilizing the system using VRE plants, avoiding the construction of thermoelectric reserves.

1. Introduction

System flexibility could be defined as "the extent to which a power system can modify electricity production or consumption in response to variability, expected or otherwise".[1] Transmission system operators (TSOs) guarantee flexibility through sophisticated control systems and the purchase of ancillary services from the dispatching services market (MSD) and from the real-time balancing market (MB). Different types of ancillary services are used to ensure the security and stability of the grid, and the total amount of generating units allowed to participate in the MSD and MB forms the reserves (i.e., available system flexibility). Ancillary services can be classified according to the time in which they must be delivered:[2] power quality and regulation (ms–5 min); spinning reserve, contingency reserve, black start (5 min–1 h); load following, load leveling/peak shaving/valley filling, transmission curtailment prevention, transmission loss reduction, unit-commitment (1 h–3 day); or listed by their regulatory functions:[3] inertial response, active power ramp rate control, frequency response, voltage regulation, fault contribution, and harmonic mitigation.

Large share of variable renewable energy (VRE) imposes higher system flexibility to resolve the increased demand/supply imbalance induced by the inherent variability/unprogrammability of the resource. The flexibility requirements for system balancing are related to "expected" variability, i.e., uncertainty about the scheduled supply that should be provided the next day by dispatchable generators. To resolve errors in forecasting demand and VRE generation on an hourly and day-ahead basis and balance the system, TSOs purchase on MSD, load-following, and unit-commitment ancillary services. In this article, for the sake of brevity, when we talk about "ancillary services," we

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The ORCID identification number(s) for the author(s) of this article can be found under https://doi.org/10.1002/solr.202200704.

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DOI: 10.1002/solr.202200704

refer only to these specific services, just as when we talk about "flexibility" we mean only that required to balance the system.

Traditionally, the main ancillary services suppliers have been large thermoelectric generators. For this reason, to address the growing demand for flexibility, the Italian capacity market is indirectly financing the construction of 19 new gas turbines with a total power of 42 GW through the market incomes since 90% of the allocated auctions involve thermoelectric capacity.[4]

On the other hand, the National Regulatory Authority (NRA) in Italy, with the Resolution no. 300/2017/R/eel issued on the May 5, 2017, according to the EU market evolution,[5] intended to begin the gradual opening of the dispatching services market to resources that have not yet been enabled, including both demand-side and supply-side (e.g., flexible renewable energy source (RES)) resources.

1.1. New Flexibility Resources

In recent years, research has proposed and studied many alternative supply/demand-side flexibility solutions other than the traditional thermoelectric reserve, some of which are ready to be implemented while others are still being investigated.[1,2,6–8]

First and foremost, improving the accuracy of the residual demand forecast could immediately lead to an imbalance and reserve reduction. Zhang et al.[9,10] ascertained that improving the PV generation and ramp forecasting could result in 25% spinning reserves cost reduction in the areas under control of the New England and California ISOs. Wu et al.[11] estimated the economic impact on energy reserves of wind and solar uncertainty and variability for the Arizona Public Service Company utility in the southwestern United States. Pierro et al.[12,13] evaluate the energy and cost benefits of accurate forecast in transmission scheduling and reserve assessment in a small region in the north of Italy. Pierro et al.[14] have also demonstrated how it is possible to reduce the volumes and costs of the 2016 Italian imbalance by an average of 15% using an accurate "state-of-the-art" photovoltaic power forecast. David et al.[15] studied the value of solar energy forecasting for a PV hybrid system bidding in the Australian energy market, finding that a 1% improvement in accuracy leads to 2% additional revenue.

Another solution to reduce system flexibility requirements is strengthening the transmission grid to reduce congestions and enable more effective sharing of dispersed flexible resources in the TSO-controlled area. For example, Kies et al.[16] showed that, in Germany at high VRE penetration level, transmission limits and congestions could reduce the expected capacity factor of wind and solar by 40% and 30%. Müller et al.[17] estimated (by the European electricity market model) the investment trade-off between transmission grid expansion, storage installation, and RES curtailment required in the EU system to reach the RES generation target at 2030 and 2050. They conclude that "optimal transmission line expansion is the preferred option in comparison to additional storage facilities." Pierro et al.[14,18] demonstrate that enlarging the PV power forecast footprint from the six market zones (in which Italy is currently divided) to the entire nation would reduce forecast errors by 25–30%. Finally, removing grid constrains enable energy markets integration, which is a very important point to obtain low energy prices and avoid arbitrage activities (see for instance the real examples reported in Pierro et al.[19]).

Another important, and one of the most studied flexibility solutions, already tested in pilot projects, consists of applying energy storages. To increase demand-side flexibility, storage can be used to shave and shift the peak load.[20,21] To improve supply-side flexibility, storage can be used to reduce the power scheduling errors of single wind or solar farm, to provide power and energy grid ancillary services as well as to reach a VRE baseload generation. Banham-Hall et al.[22] and Delfanti et al.[23] coupled a wind and PV farm to a battery storage energy system. Banham-Hall et al. studied a specific power controller to allow wind frequency regulation services and optimal hour-ahead scheduling, but they did not study whether or not this could be economically feasible. Delfanti et al. used storage to improve PV power forecast accuracy, but they conclude that it could be economically justifiable only when the storage costs will become lower than 154 € kWh^{-1}. Perez et al.[24] proved how it would be possible, in a near future, to reach ultrahigh VRE penetration by providing baseload wind solar generation at competitive costs. In the same direction, Perez et al.[25] and Pierro et al.[26] proposed a USA–Italy scalable strategy for a low-cost RE transition starting from perfect forecast (i.e., removing prediction uncertainty) to wind solar firm generation (i.e., removing variability and intermittency). The same authors[27] analyzed the impact of flexible PV fleet displacement on the previous mentioned strategy considering different levels of PV penetration and flexibility. Cebulla et al.[28] applied the linear model REMix to compute the storage power and energy capacity in the EU to reach 89% of the RE energy share. They also analyzed optimal displacement and technological storage mix according to the wind and solar availability of each EU country. In particular, they found hydrogen and battery storage more suitable, respectively, for wind and PV-based load generation. However, the results for Italy might not be reliable, as a much more realistic scenario that considers an extensive use of storage for baseload VRE generation could be found in Pierro et al.[26] (only electric sector) or in Prina et al.[29] (considering also heat demand). Sharma et al.[30] reviewed the use of forecasting in energy storage, including energy storage and operational reserve, renewable energy integration, and market applications. Xu et al.[31] developed a predictive control strategy to optimize the use of energy storage and renewable generation for a distribution load aggregator, showing that it also contributes to improving the reliability of the bulk power system during loss-of-load events. The interesting study of Black[32] calculates the technical-economic benefit of using storage to improve system flexibility (decreasing primary/secondary reserve) and to increase the wind energy share in the UK.

Also, VRE curtailment can improve system flexibility as reported in Nicolosi paper.[33] Müller et al.[17] showed that in the EU, VRE curtailment could reduce the grid net transfer and storage capacities costs required by 2030/2050 RES share targets. Jacobsen et al.[34] in their notable work, provided a classification of curtailment events in terms of reasons, involuntary, voluntary, and rationale. In this direction, Perez et al.[24,26] demonstrated that VRE overbuilt and proactive curtailment (voluntary curtailment enacted by the TSO to meet the regional load profile) are essential to reduce the amount of storage needed to reach a firm renewable generation at reasonable costs. They showed that wind/solar curtailment is the key factor to reach, in a near future, an ultrahigh RES penetration at or below the current energy costs.

Demand-side flexibility is also another option currently studied. It involves the ancillary services that could be provided by different electrical sectors (sectors coupling)[35]: consumption units enable to reduce or improve their electrical demand (as for industrial process), power to heat, power to hydrogen, electric vehicles smart, and bidirectional charging. However, demand-side flexibility will require extensive electrification of this readily modulable electrical energy demand, a process that is only in its early stages, so the main demand-side flexibility is still only in the technical-economic research phase.[36]

In contrast, a very important source of flexibility, ready to be implemented on large scale, is the use of several distributed resources managed by a single company (aggregator) as a single medium/large virtual power plant (VPP). Indeed, tests in different countries[37] have shown that aggregators can act as balancing service providers (BSPs) as well as existing thermoelectric generators. The VPP embeds many of the flexibility measures mentioned above, but small in size and spread over a wide area. This is also a preview of how PV/wind/BESS systems should operate. Firm power generation at scale will require full virtualization of the system (all actors contribute small and large, centralized, and decentralized storage, etc.).

The Italian Transmission System Operator (Terna), according to the above-mentioned NRA resolution and the ongoing research, launched several pilot projects to allow the participation to the MSD of the following resources: 1) variable/nonprogrammable renewable sources; 2) storage systems; 3) distributed generation; and 4) flexible demand. These projects mainly include aggregators that manage different types of VPPs, the most promising of which are mixed enabled virtual units:[38] aggregate of nonenabled relevant and nonrelevant (both programmable and nonprogrammable) production units, consumption units, and storage systems, including charging stations for electric vehicles. At the same time, the Italian TSO has planned activities to strengthen exchanges between market areas for greater integration of renewable energy sources along with resolving critical congestions, integrated security management of the national transmission grid (NTG), and increasing widespread control of the grid.[39]

However, the geopolitical consequences of the current war require accelerated large-scale implementation of these alternative flexibility approaches to traditional natural gas generators.

1.2. Aim of the Work

In this work, we suggest two simple and immediately actionable flexibility solutions based on “flexible” VRE systems: PV/wind power plants (utility scale or VPPs) equipped with smart inverters, central power plant controllers (PPCs), and battery energy storage systems (BESS). Flexible VRE systems can be considered for all intent and purpose to be counted as secondary reserve operationally equivalent to current used thermoelectric generators. They can be managed to supply load following and unit-commitment ancillary services. Downward regulation can be provided by VRE proactive curtailment, while upward regulation is obtained by BESS power injection. While flexible VRE regulation is perfectly feasible from a technical standpoint, it is still unclear how cost effective it will be because of the high cost of batteries and of the current energy prices on the MB.[40,41]

The final goal of the study is to show how TSOs could cost effectively manage a fleet of flexible PV/wind systems to provide secondary regulation services and reduce imbalances and flexibility requirements induced by VRE penetration. We test two different regulation strategies using real load, VRE generation data, and energy price signals provided by the Italian TSO. The first strategy (solar regulation) uses flexible PV systems with the possibility of nighttime storage grid charging to reduce the daytime imbalance. The second strategy (VRE regulation) involves the ancillary services provided by both flexible photovoltaic and wind power systems. We assess the effectiveness of these flexibility solutions in Italy at the current and future VRE penetration levels in the present case where imbalance is evaluated and resolved on each of the market zones (into which Italy is divided), and in the case where the strengthening of the national transmission grid allows for a single national balancing area (as in the strategic plan of the Italian TSO).

1.3. Novelty of the Work Compared to the Literature

In this article, instead of taking the point of view of a single VRE producer who wants to provide ancillary services, as in some of the aforementioned works,[7,15,40,41] we take the point of view of the TSO who capable of controlling a distributed fleet of flexible VRE plants for system balancing. Compared with the study, Black et al.[32] evaluated the added value of storage in reducing thermoelectric reserves and improving the share of wind power, in this paper, we show how these reserves can be entirely replaced by flexible VRE systems. In addition, we show that not only storage but also proactive curtailment (i.e., implicit storage) plays a key role in increasing system flexibility, as also pointed out in some of the papers mentioned above.[14,24,26,34]

While solar regulation strategy was already explored in our previous work,[42] here we also test the effectiveness of VRE regulation via photovoltaic and wind flexible systems with storage recharged by renewable energy only.

The second novelty of this work is to go deeply inside the operating principles of the VRE regulation and the concept/properties of “implicit” storage that enable VRE plants to provide also upward regulation services reducing or even without the need of storage.

The third innovative aspect concerning Pierro et al.[42] besides uses a more accurate net load forecasting, is to compare imbalance and flexibility requirement reduction that can be achieved by solar/VRE regulation strategies on each Italian market zones with the reduction achievable by coupling solar/VRE regulation with grid reinforcement aimed at completely removing capacity transit constraints between market areas. Doing so, we confirm the findings of Muller[17] that support the importance of strengthening the transmission network to increase system flexibility and improve the RES share.

The last innovative aspect is the proposed regulatory framework and business model that allow solar/VRE regulation to be economically competitive with the current business-as-usual imbalance costs.

1.4. Organization of the Paper

This paper is organized as follows: 1) In Section 2, we briefly introduce the main features of European and Italian imbalance regulatory framework; 2) In Section 3, we explain the principles of thermoelectric, VRE regulation, and VRE regulation and implicit storage; 3) In Section 4, we describe the methodology followed in our investigation; 4) In Section 5, we explain the market and regulatory framework used to compute the VRE costs; 5) In Section 6, we describe and discuss our results; 6) In Section 7, summary and conclusions are reported.

2. Italian Imbalance Regulatory Framework and Ancillary Services Market

Although there are several bidding zones in Italy, this national territory is characterized by a unique control area, where the Terna SpA, the TSO, is responsible for maintaining the system operation security.

The Terna dispatching activities aimed at issuing provisions for the coordinated use and operation of production plants of the transmission grid and of ancillary services. Load-following and unit commitment ancillary services are some of the regulation services carried out by BSPs that manage flexible resources (relevant UPs) enable to bid on the balancing service market (MSD) and are required by Terna to resolve the imbalance between the demand net of VRE generation (residual demand or netload) and the supply scheduled on the DAM

$$\Delta P_{\text{imb}} = P_{\text{supply}}^{\text{scheduled}} - P_{\text{netload}} = P_{\text{netload}}^{\text{for}} - P_{\text{netload}} \tag{1}$$

where ΔP_{imb} is the energy imbalance at the hour h and P_{netload} is the netload ($P_{\text{Netload}} = P_{\text{load}} - P_{\text{PV}} - P_{\text{wind}}$). The superscript "for" means "forecast."

In case of positive imbalance (higher scheduled supply than netload), Terna orders to BSPs to decrease the electricity injected into a dispatching point (downward regulation). In this case, the unproduced generation is considered sold to Terna to the BSPs, and its sale price on MSD is lower than the day-ahead baseload price ("Single National Price," PUN). In contrast, in case of negative imbalance (lower scheduled supply than netload), Terna order to BSPs to increase the electricity injection (upward regulation) and acquires this additional energy on MSD at a price higher than PUN.

The imbalance volume and cost derived by the energy exchanged on MSD are defined as following

$$\text{Imbalance volume} = \sum_{h=1}^{Nh} |\Delta P_{\text{imb}}(h)| \tag{2}$$

$$\text{Imbalance cost} = \sum_{h=1}^{Nh} [\delta_h * \max\{\text{PUN}, \boldsymbol{P}_{B\uparrow}\} * |\Delta P_{\text{imb}}(h)| + (1-\delta_h) * \min\{\text{PUN}, \boldsymbol{P}_{B\downarrow}\} * |\Delta P_{\text{imb}}(h)|] \tag{3}$$

where PUN, $\boldsymbol{P}_{B\uparrow}$, and $\boldsymbol{P}_{B\downarrow}$ are the DAM and MSD upward, downward energy prices; δ_h is a Boolean function that is equal to zero if ΔP_{imb} (h) is positive or is equal to one if ΔP_{imb} (h) is negative; and Nh is the number of hours in a considered period (1 year in this work).

The maximum amount of load-following and unit commitment ancillary services that Terna has to set up for the next day to balance the system is called tertiary replacement reserve and is dimensioned using a symmetric band (for up/downward regulation) evaluated through the 99.7% order quantile of the netload forecast errors.[43]

Therefore, we define the system flexibility required to resolve the imbalance related to incorrect demand scheduling (i.e., the maximum amount of tertiary replacement reserve) as

$$P_{\text{flexibility}} = Q_{99.7}(|\Delta P_{\text{imb}}|) \tag{4}$$

evaluated over the imbalances of one year.

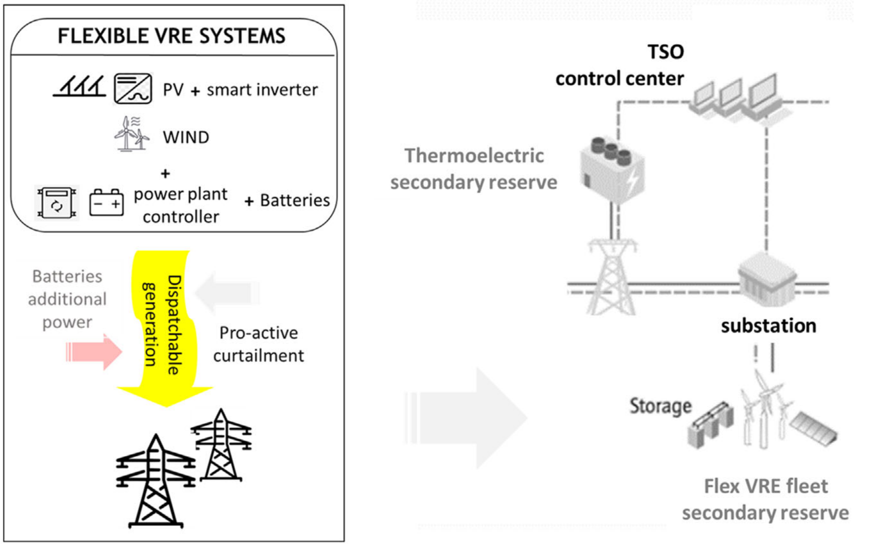

Figure 1. Flexible VRE systems scheme.

3. Imbalance Regulation via Flexible VRE Plants and Implicit Storage

VRE plants are not dispatchable since they cannot generate energy on demand. However, the technology to make them dispatchable generators is already on the table. In fact, PV and wind power plants equipped with smart inverters, central power controllers, and BESS can provide programmable, base load-tracking generation 24/365,[24–26] as well as load following and unit commitment ancillary services.[14,42] Therefore, these plants can be considered as secondary reserves for all intents and purposes (**Figure 1**).

Presently, the balancing between residual demand (net load) and scheduled supply (net load forecast) is mainly done by the ancillary services provided by natural gas thermoelectric generators that have a faster response time. **Figure 2**a shows how the TSO manages these plants to fill the gap between the netload (load net of PV and wind generation) observed and predicted

$$\mathrm{NL} = \mathrm{NL}^{\mathrm{for}} + \delta|\mathbf{IMB}^{\uparrow}| - (1-\delta)|\mathbf{IMB}^{\downarrow}| \tag{5}$$

where NLand $\mathrm{NL}^{\mathrm{for}}$ are the net load observed and predicted, $|\mathbf{IMB}^{\uparrow}|$ and $|\mathbf{IMB}^{\downarrow}|$ is the energy required for upward and downward system regulation, with $\delta = 1$ if $\mathrm{NL}^{\mathrm{for}} < \mathrm{NL}$ or $\delta = 0$ if $\mathrm{NL}^{\mathrm{for}} \geq \mathrm{NL}$.

If the scheduled supply (net load forecast) is less than the residual demand, the TSO provides upward regulation ($|\mathbf{IMB}^{\uparrow}|$) by sending dispatching orders to BSPs. In this case, the production units enabled to participate in ancillary services market increase their generation to meet the demand. Vice versa, if the scheduled supply exceeds the residual demand, the TSO provides downward regulation ($|\mathbf{IMB}^{\downarrow}|$) ordering to BSPs to decrease their generation.

Flexible VRE systems can be managed by the TSO in the same way as thermal power plants, either by feeding BESS energy into the grid for upward regulation or by proactively curtailing solar/wind generation for downward regulation or to recharging the storage (when the imbalance is positive). In this case, the effect of flexible VRE regulation is to adapt the observed net load to the forecast, either by increasing the residual demand through limiting VRE generation or decreasing the residual demand through increased VRE generation (BESS additional power)

$$\mathrm{NL}^{\mathrm{for}} = \mathrm{NL} - [\delta|\mathbf{BESS}^{\uparrow}| - (1-\delta)|\mathbf{VRE}^{\downarrow}|] \tag{6}$$

where $|\mathbf{BESS}^{\uparrow}|$ is the energy provided by batteries for upward regulation and $|\mathbf{VRE}^{\downarrow}|$ is the VRE proactive curtailment required for downward regulation or for BESS recharging.

Figure 2b shows how the TSO can curtail the PV generation or inject energy from the batteries to resolve the diurnal imbalance.

After flexible VRE regulation, the residual demand will be increased of the quantity

$$\begin{aligned}\Delta \mathrm{NL} &= \sum_{h=1}^{Nh} [(1-\delta_h)|\mathbf{VRE}_h^{\downarrow}| - \delta_h|\mathbf{BESS}_h^{\uparrow}|] \\ &= E_{\mathrm{VREcurt}} + E_{\mathrm{VRE2BESS}} - E_{\mathrm{BESS2grid}}\end{aligned} \tag{7}$$

where E_{VREcurt}, E_{VRE2BESS}, and $E_{\mathrm{BESS2grid}}$ are the yearly energy volumes of the VRE curtailment of the VRE used to recharge the batteries and of BESS additional power injected into the grid. This quantity can eventually be increased of the energy drawn from the grid to recharge the storage if needed to improve the effectiveness of the BESS upward regulation.

Even if the technologies are already on the table, it is very likely that, considering the current cost of batteries, it is not profitable operate flexible solar and wind farms in this fashion.

VRE plants (without batteries) can easily provide downward regulation services by proactive power curtailment, but this is simplest and least expensive part of the balancing job. Virtually, these plants can provide also upward regulation services as pointed out in the 2011 IEA report[1]: "It is also possible for VRE power plants to be backed down to below maximum output at a given time, so that they can ramp upwards again when necessary to provide balancing services." Nevertheless, it is not clear when and how much these plants should be kept unloaded from their rated capacity to provide upward regulation services.

In this work, we propose a solution of this problem based on a probabilistic under forecast of the VRE generation. As depicted

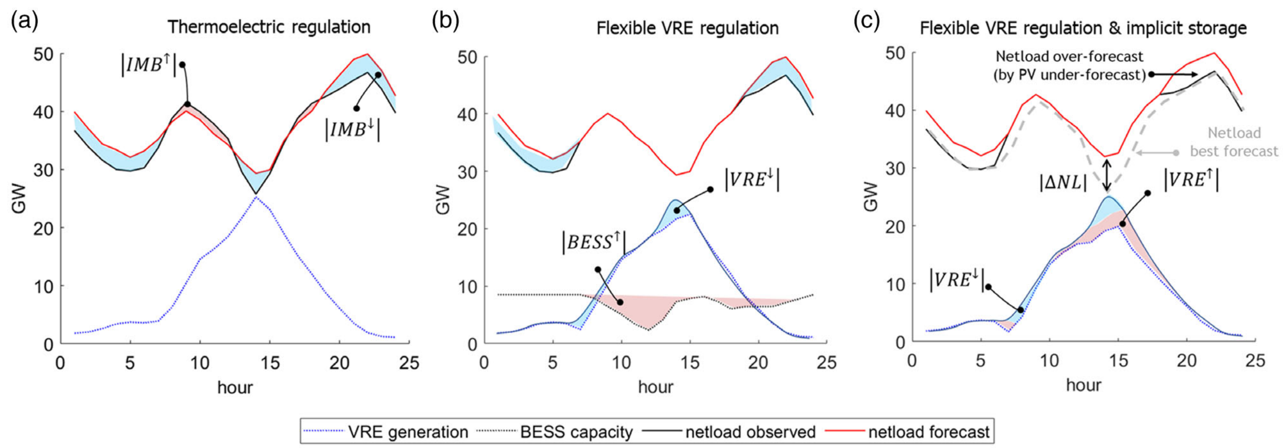

Figure 2. Imbalance regulation a) via thermoelectric generators, b) via flexible VRE systems, and c) via flexible VRE systems and implicit storage.

in Figure 2c, if the TSO uses of an appropriate underprediction of VRE generation (e.g., a low forecast quantile—instead of the most accurate prediction), it will results in a more likely scheduled oversupply which could still be resolved by reducing VRE generation

$$\mathrm{NL}^{\mathrm{for}} = \mathrm{NL} - [\delta(|\Delta\mathrm{NL}| + |\mathbf{VRE}^{\uparrow}|) - (1-\delta)|\mathbf{VRE}^{\downarrow}|] \quad (8)$$

where $|\Delta\mathrm{NL}|$ is the net load over prediction and $|\mathbf{VRE}^{\uparrow}|$ is the additional proactive curtailment need to adapt the netload observed to the over predicted.

The additional curtailment produced by the VRE underforecast replaces storage upward regulation services ($|\mathbf{BESS}^{\uparrow}|$), so that underforecast/proactive curtailment ($|\Delta\mathrm{NL}| + |\mathbf{VRE}^{\uparrow}|$) act as an "implicit" storage. In this way, upward regulation could be provided by VRE curtailment with a reduced amount or even without the need of storage (as shown in Figure 2c).

It is worth remarking that, with flexible VRE regulation, instead of decreasing the programmed thermoelectric supply by downward ancillary services, the residual demand is increased (via curtailment of VRE) to meet the predicted netload, while the thermoelectric supply remains unchanged. VRE generation losses are the price to be paid for converting variable/unprogrammable renewable energy into more predictable but higher residual electrical demand (that can be easily supplied by the existing baseload thermoelectric park). Furthermore, the additional proactive curtailment ($|\mathbf{VRE}^{\uparrow}|$) enabled by VRE underforecast (implicit storage) is the additional environmental cost of stabilizing the system using upward regulation by flexible VRE systems.

In this work, we propose two different strategies to reduce the system imbalances and the system flexibility requirements both based on VRE ancillary services and implicit storage.

The first strategy uses a suitable dimensioned flexible PV fleet (utility-scale/medium size or VPP) automatic controlled directly by the TSO (as the current secondary reserve) to reduce the diurnal imbalance. We call this strategy "solar regulation," and **Figure 3**a shows how it works. When the imbalance is negative (residual demand exceeds the scheduled supply), TSO increases the supply by injecting additional power from the BESS of the flexible solar systems to resolve the diurnal imbalance. Conversely, if the imbalance is positive (more scheduled supply than demand), the TSO reduces the generation fed into the grid by the flexible fleet either by recharging storages, or by proactively curtailing their generation. Since the state of charge of the batteries of flexible PV systems is known at the

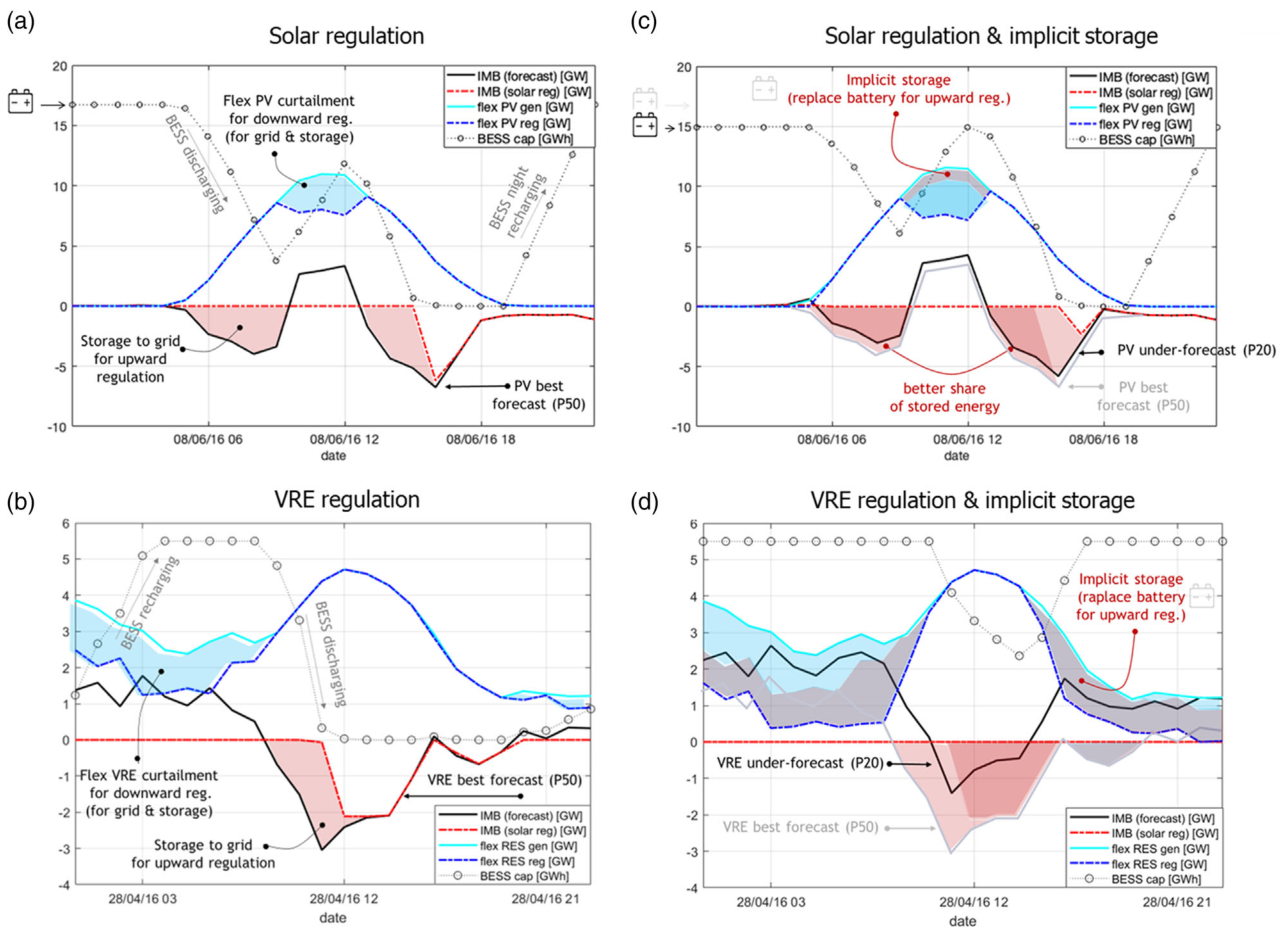

Figure 3. Imbalance regulation strategies. a) Solar regulation via the ancillary services provided by a flexible PV fleet; b) VRE regulation via the ancillary services provided by a flexible PV-wind fleet; c,d) solar/VRE regulation strategies coupled with implicit storage.

beginning of the night, the TSO can easily plan how to recharge the storages during the night hours without using fast thermoelectric reserve.

The second strategy uses a fleet of flexible PV and wind systems as secondary reserve, so we call "VRE regulation."

As depicted in Figure 3b, the VRE fleet is managed by the TSO exactly as the previous case except that the batteries are recharged only by the flexible systems generation when the imbalance is positive.

If the installed storage capacity is not enough, the residual imbalance after solar/VRE regulation should be completely resolved by thermoelectric secondary reserve.

To reduce this residual imbalance after solar/VRE regulation in both the strategies, we also use implicit storage, i.e., a suitable PV/wind underforecast/proactive curtailment.

Figure 3c shows how, considering the same imbalance reduction of Figure 3a, the use of implicit storage not only decreases the required BESS capacity but also provides a better share of the stored energy. Conversely, Figure 3d shows that, considering the same flexible fleetsolar/wind and BESS capacities of Figure 3b, the use of implicit storage can play a key role on the effectiveness of regulation and on the VRE capability of storage charging. Indeed, in this case, the ancillary services provided by same flexible PV and wind systems of Figure 3b can completely resolve the imbalance and recharge the storage.

In the case, we want to size the flexible VRE fleet to reach a specific residual imbalance target, as in Pierro et al.[42] the use of implicit storage reduces the BESS requirement and thus the imbalance costs related to the CAPEX and OPEX of the storage.

In this case, implicit storage acts in concert with a given BESS capacity of the flexible PV/wind systems, increasing the upward regulation services that the fleet can provide. In any case, the use of suitably dimensioned implicit storage reduces the need for upward regulation services in favor of considerably less expensive downward services, leading to additional savings in imbalance costs. Furthermore, implicit storage and proactive curtailment in general help to prevents/reduces VRE overgeneration (i.e., the VRE energy that should be redispatched or reactively curtail anyway). This means that VRE regulation reduces reverse power flows events and grid congestions between the different market zones, thereby increasing the resiliency of renewable energy use.

Finally, because underprediction of VRE generation implies a more efficient share of stored energy, makes daily cycles smoother, reduces BESS utilization (fewer negative imbalance events), and reduces the frequency of high C-rates (Figure 3d), implicit storage increases the BESS lifetime. On the other hand, this implies that VRE regulation and implicit storage require BESS capacity that must be always available but that is not used most of the time. For example, using the best prediction of VRE generation, storage is used for 50% of the annual hours (negative imbalance events occur 50% of the time), while using a strong VRE underprediction (5th quintile prediction), additional BESS energy is needed for only 20% of the total annual hours.

It is also worth noting that the use of implicit storage could be useful as long as the storage capacity is not sufficient to provide all the required upward regulation services, otherwise it must be obviously avoided. This means that the level of under prediction should be carefully tuned according to the available BESS capacity.

4. Methodology

The main objective of this work is to assess the potential for imbalance mitigation via ancillary services provided by a fleet of flexible solar and wind systems in Italy at current a future VRE penetration levels. We also assess the impact of solar/VRE regulation on Italian imbalance costs, flexibility requirements, and curtailment of VRE generation. We performed this study both for the case in which the imbalance is evaluated independently in each of the six Italian market zones and for the case in which the imbalance is evaluated on the entire country. The former requires regional individual forecasts in each market zones, while the latter only requires one country-wide forecast. The latter also implies that solar/VRE regulation strategies would be coupled with transmission grid reinforcement aimed at completely removing capacity transit constraints among Italy's regional market zones. Note that the Italian TSO has already planned extensive interventions to strengthen exchanges between market areas aimed at better sharing of generation from RES and production of the most efficient generating units to be used for baseload generation and system balancing.[39]

To this end, we adopted the following methodology based on three steps: 1) We utilized 2016 real hourly load, PV and wind generation hourly data, and real DA and Balancing prices signals of each market zone provided by the Italian TSO (Terna Srl).[44] Then, we applied previously developed load, PV, and wind power forecast models [The description of forecast models is beyond the scope of this article and will be published in a dedicated paper. However, insights into the solar forecast model can be found in Pierro et al.[49]] to perform the day ahead netload predictions and we computed the current and future imbalance volumes, costs, and system flexibility requirements assuming capacities growth scenario proposed by the Italian TSO[45] and the Bloomberg BESS cost evolution[46] (**Figure 4**). We assume that the hourly profiles of load, PV, and wind generation remain the same as in 2016 but are rescaled according to the NT scenario to take into account the evolution of the RES penetration and the annual growth of the electric demand. This is a simplifying assumption since the load profile is expected to change in future due to the electrification of many sectors (residential, transports, etc.), and, to a lesser extent, the PV/wind generation profiles obviously changes years by years. However, it should be kept in mind that the imbalance between residual demand and scheduled supply depends entirely on the accuracy of the netload predictions, which is also expected to improve in the future from evolving forecasting techniques. In this respect, our assumption can be considered to be conservative. The NT-scenario of Terna is consistent with the "National Trend" developed by ENTSO-E and ENTSOG for the European Development Plan (TYNDP) 2020 and updated the final version of the December 2019 National Integrated Energy and Climate Plan (PNIEC).[47] The main differences with the NT-scenario are that we assume the BESS used for PV/VRE regulation to be essentially utility-scale storage systems and the allocation of capacities between different market zones. We allocate solar resources according to an optimization

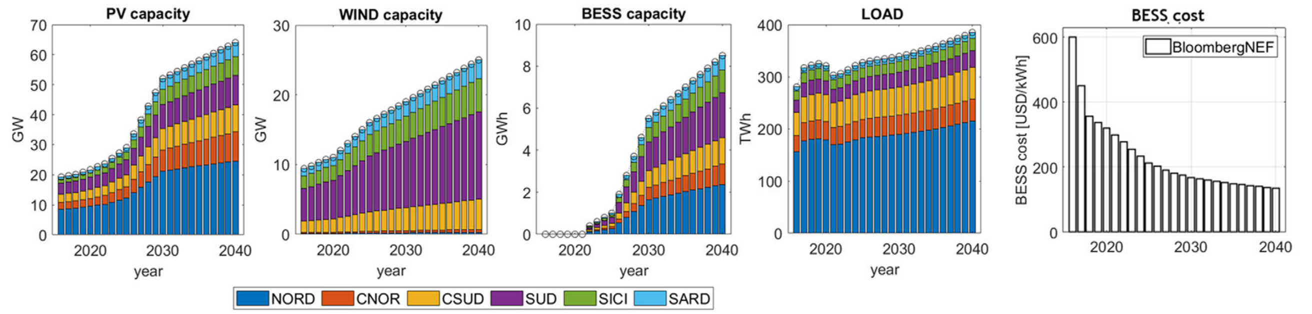

Figure 4. NT-scenario developed by the Italian TSO and Bloomberg NEF learning curve of utility scale lithium battery energy storage systems.

procedure reported in Prina et al.[48] wind capacity based on the current zonal proportion [As wind sites are essentially those currently used and planned capacity growth can be mainly obtained through repowering or expansion.], BESS on the basis of PV and wind placement, and finally load based on current proportion of the zonal demand. 2) We defined a two different scenario of growth of flexible VRE fleets enabled to provide ancillary services and of underforecast levels. The first scenario assumes that 20% of the new solar capacity will be flexible PV systems equipped with 50% of the planned storage capacity (**Figure 5**). The 20% figure was chosen, as this is the current capacity of utility-scale PV parks. We also used an implicit storage obtained by 15th quantile underforecast until 2029 and 20th quantile underforecast until 2040. These underprediction levels were chosen to achieve almost the same residual imbalance (after applying solar regulation) regardless of the expected VRE penetration. The second scenario assumes that all current and future wind farms are transformed or constructed as flexible systems and cooperate with previously sized flexible PV fleet to provide regulation services (**Figure 6** and 6b). Since wind plants are almost all part of utility-scale parks, which are much less distributed than solar, it would be easier to turn them into flexible systems. In this case,

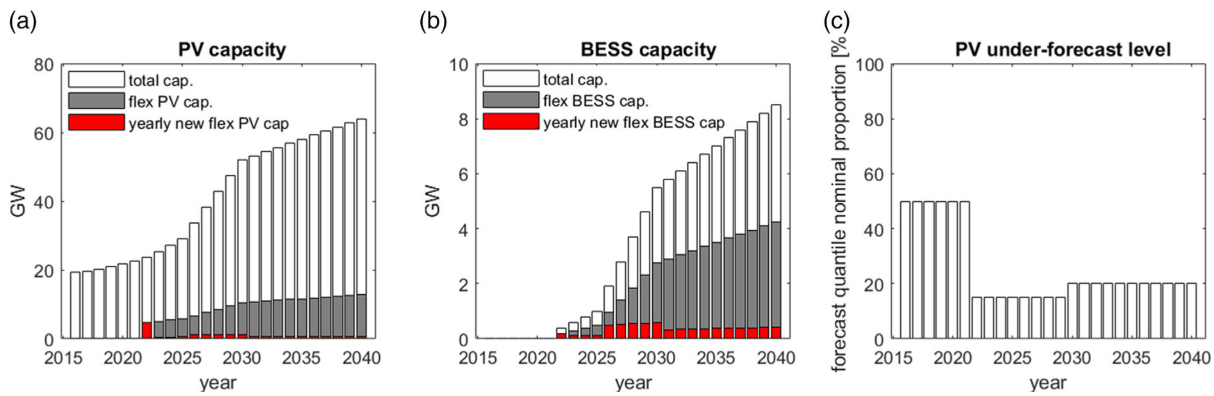

Figure 5. a) Growth scenario of the flexible PV fleet capacity dedicated to solar regulation; b) growth scenario of the flexible PV fleet storage capacity; c) PV underprediction levels used to improve upward ancillary services of flexible solar fleet.

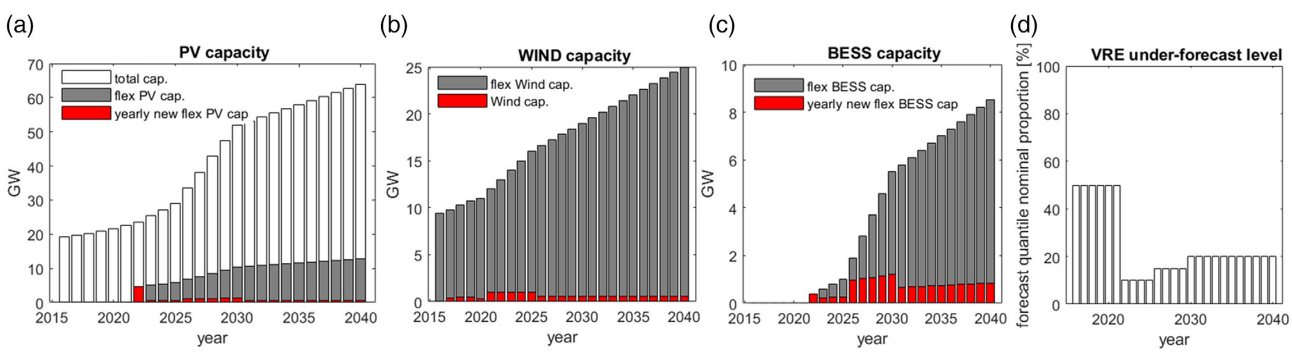

Figure 6. a,b) Growth scenario of the flexible PV/wind fleet capacity dedicated to VRE regulation; c) growth scenario of the flexible VRE fleet storage capacity; d) VRE underprediction levels used to improve upward ancillary services of flexible solar fleet.

all the planned BESS capacity was designed to provide regulatory services (Figure 6c). Also in this scenario, we used different implicit storage levels resulting from the use of 10th quantile underforecast until 2025, 15th quantile underforecast until 2029, and 20th quantile underforecast until 2040. As in the first scenario, implicit storages have been chosen to obtain the same residual imbalance regardless the VRE penetration. 3) We simulate the action of solar/VRE regulation services (through the previously dimensioned solar and wind flexible fleet and implicit storage) to reduce current and future annual imbalance hourly profiles (obtained by the previously calculated netload forecast). Then we evaluate the benefit of the regulation strategies in terms of residual imbalance volumes (that should be resolved by thermoelectric reserves), flexibility requirement reductions, imbalance regulation costs, and VRE curtailment.

5. New Market and Regulatory Frameworks for Flexible VRE Systems

To compute the costs of the of the ancillary services provided by the solar/wind flexible fleet and implicit storages, we proposed a new market and regulatory frameworks: the owners/producers of the flexible PV/wind plants sell the energy only on the day-ahead market, and the TSO pays the proactive curtailment at the day-ahead energy prices. Therefore, flexible PV plants are allowed to provide ancillary services but still not allowed to participate to the MB. Furthermore, the Italian government (through the TSO) also pays the BESS CAPEX and OPEX and the night storage recharging (in case of PV regulation).

With this business model, we will show that the current business as usual (BAU) imbalance costs (that are shared among the rate-payers) are comparable with the ones obtained by our PV/VRE regulation strategies.

Moreover, this is a win–win economic strategy since the TSO would reduce its investment in flexibility measures while the owners of the flexible solar/wind plants will sell all their generation at the national day-ahead price without any charge for their imbalances (i.e., as if they had provided a perfect scheduling of their production). Moreover, the producers will have payback via state funds also all the storage-related expenses increasing the value of their plants.

In contrast, even if VRE parks will be allowed to provide ancillary services (as required by the EU regulatory reform), it is highly likely that it will still be much more profitable for utility-scale VRE producers/VRE aggregators to sell the energy on the day-ahead market (DAM) then convert their systems into flexible and bids on the ancillary services market. This is because, in the ancillary services market, the curtailment for downward regulation is paid at lower prices than for DAM, while, even if the upward regulation provided by BESS is paid at higher prices than for DAM, at the current costs of BESS, it is very likely that the economic returns do not justify the investment.[40,41]

6. Results

In this section, we describe the results achieved simulating the action of solar/VRE regulation via the load-following and unit commitment ancillary services provided by the solar and wind flexible fleet (previously sized) and implicit storage. Here, we assume that the fleet is uniformly distributed inside each market zone, noting that results do not change appreciably if we randomly chose the locations of the flexible solar plants, as we have shown and discussed in Pierro et al.[42]

In Section 6.1, we show the imbalance reduction that can be achieved by solar/VRE regulation with implicit storage in each market zone (as currently performed by the TSO).

In Section 6.2, we report the imbalance volumes/costs reductions and proactive curtailment that can be achieved by solar/VRE regulation in a future case in which grid reinforcement allows the use of the netload prediction directly performed at Italian level.

In Section 6.3, we compare the results obtained in the current case (forecast footprint at market zone level) and in a future case (forecast footprint at extended at national level).

6.1. Current Case: Solar/VRE Regulation with Implicit Storage Using the Netload Forecasts of Each Market Zones

Figure 7 shows the current and futures annual imbalance volumes that can be achieved in each market zone by our advance forecast methods and the residual imbalance volume (that has to be resolved by thermoelectric reserves) after applying solar/VRE regulation with implicit storage strategies.

In all the market zones, solar regulation can limit the growth of the imbalances induced by increasing penetration of VRE sources, so that the residual imbalance volumes expected in the future are approximately equal to the current imbalance value. It is slightly more effective in the North (NORD) and center-North (CNOR) zones where solar capacity is dominant with respect to wind (Figure 4).

Vice versa solar and wind regulation strategy is extremely effective in the other zones almost eliminating the residual imbalance regardless the VRE penetration expected in the future.

6.2. Solar/VRE Regulation with Implicit Storage Using the Forecast of the Country-Wide Italian Netload

It is well known that enlarging the forecast-controlled area the accuracy of solar/wind predictions decreases due to the so called "smoothing effect."[49] This obviously implies the reduction of required flexibility and imbalance volumes. However, as mentioned above, the extension of the forecast footprint will only be possible when all the transmission bottlenecks between the market zones are completely removed (as planned by the Italian TSO).

Figure 8 shows the current and future imbalance volumes achieved by our best forecast (P50%) together with the residual imbalance volumes after applying our solar/VRE regulation strategies with an implicit storage obtained by the underforecast (PX) reported in Figure 5c and 6c.

Both the strategies reduce the imbalance volumes so that the residual imbalance after solar/VRE regulation is expected to remain approximately constant regardless the growing VRE share. In particular, proactive curtailment of solar and wind

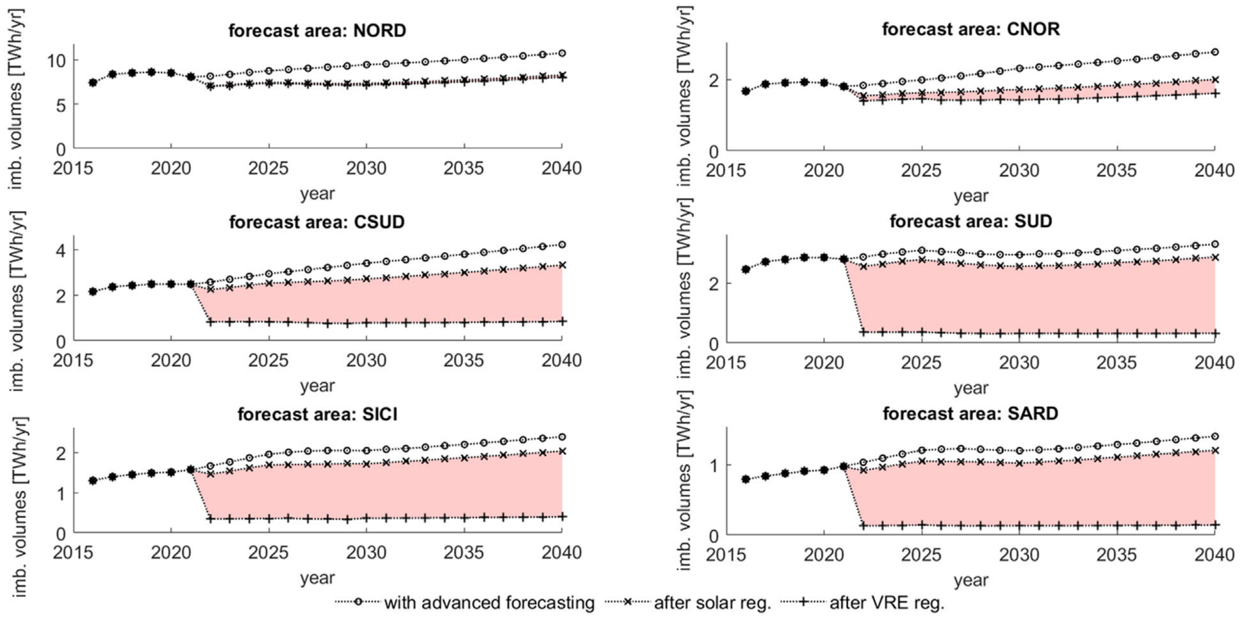

Figure 7. Current and future imbalance volumes in each market areas obtained by our advanced forecasting and residual imbalance volumes achieved after applying solar/VRE regulations.

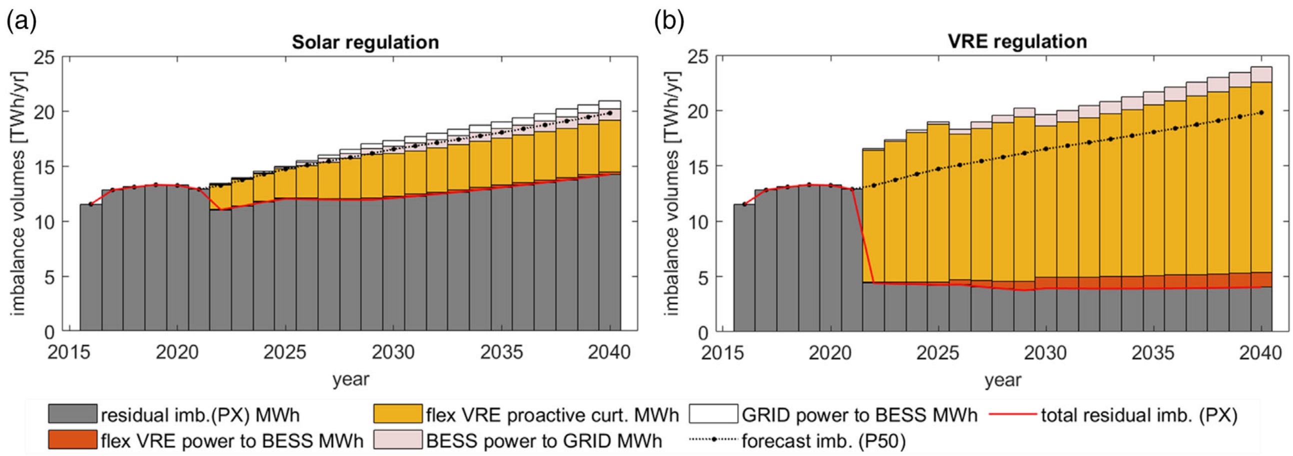

Figure 8. Current and future imbalance volumes obtained by our best prediction (P50) of the national netload (black dots line) and residual imbalance volumes achieved after applying a) solar regulations and b) VRE regulations with an implicit storage obtained by a given solar/wind underforecast (PX) (red line).

flexible fleet generation plays the lion's share in providing downward and upward regulation services, while upward regulation obtained by BESS has a rather small contribution. This is because the capacity of the storage units dedicated to balancing the system is significantly undersized.

Figure 9 shows the fraction of the proactive curtailment used to provide downward and upward regulations. In the case of solar regulation, almost a third of the curtailment is used as implicit storage for upward regulation, while in the case of VRE regulation implicit storage becomes the half of the total curtailment.

Figure 10 shows the costs of solar/VRE regulation with implicit storage computed according to our business model and the business as usual costs (BAU) of the imbalance obtained by our forecast and the BAU residual imbalance costs after applying the proposed balancing strategies. The major costs of our regulation strategies are the proactive curtailment (remunerated at the DA price) followed by the BESS CAPital Expenditure (CAPEX).

6.3. Cost–Benefit of Solar/VRE Regulation Strategies with Implicit Storage without and with Grid Reinforcement

Figure 11 shows the benefit in using our regulation strategies both in the current case of computing the Italian imbalance as the sum of the single market zones and in the case of using

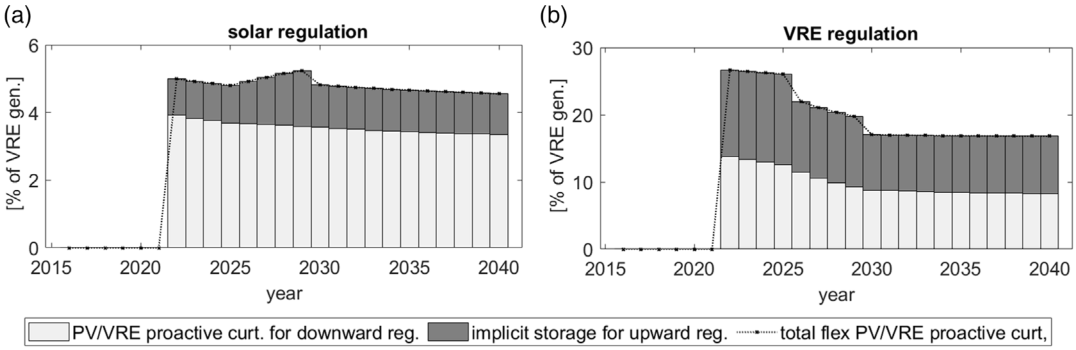

Figure 9. a) Proactive curtailment used in PV and b) VRE regulation strategies for downward and upward regulation services (implicit storage).

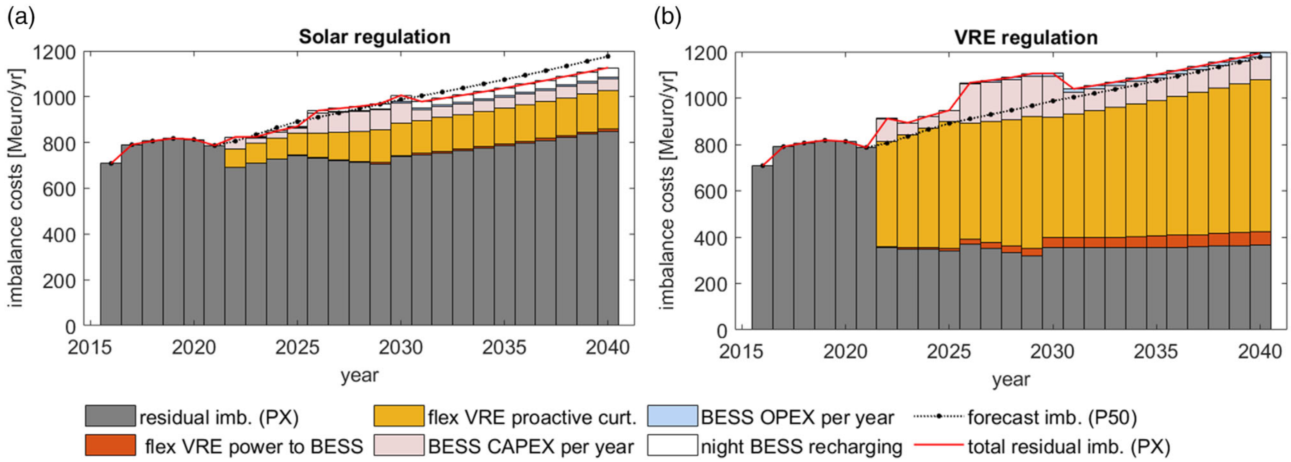

Figure 10. Current and future imbalance costs obtained by our forecasting of the national netload (black dots line) and residual imbalance costs achieved after applying a) solar regulations and b) VRE regulations and implicit storage (red line).

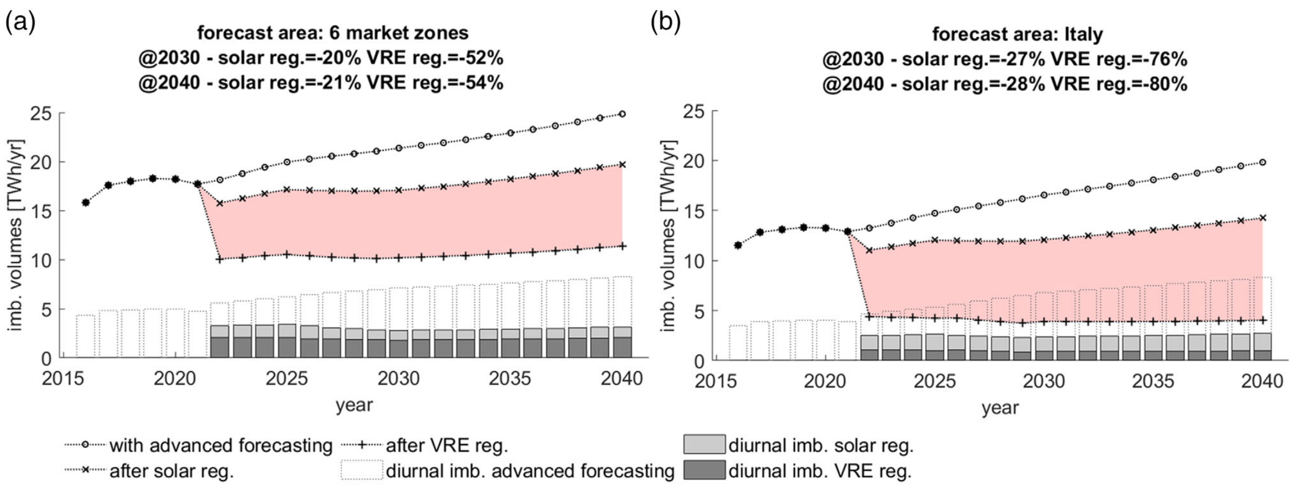

Figure 11. Imbalance achieved by our forecast (dotted line), margin of imbalance reduction obtained by solar/VRE regulation-implicit storage strategies (red area) and diurnal imbalance reduction both a) in the case of the imbalance resulting from the six market zones forecast and b) in the case of a unique national prediction.

grid reinforcement to enable the use of a unique national balancing area. In the former case, the margin of reduction in imbalance volumes achievable through solar/VRE flexible fleet ancillary services with implicit storage is about 20–50% at 2030–2040. Coupling solar/VRE regulation-implicit storage strategies with grid reinforcement the reduction margin can be increased to at least 27–75% by 2030–2040. Thus, enabling the enlargement of the forecast footprint at national level notably increases the benefit of our strategies especially in the case of VRE regulation. Figure 10 also shows the diurnal imbalance reduction. By 2030–2040, solar regulation halves daytime imbalances while is almost completely remove by the ancillary services provided by the flexible solar-wind feet.

Figure 12 shows that the imbalance costs of solar/VRE regulation with implicit storage (obtained by our business model—Section 3) together with the costs to completely resolve the residual imbalance through traditional reserve are very similar to the business-as-usual ones. The main difference appears before the 2030 due to the storage CAPEX (resulting from the rapid growth of the BESS capacity that has been planned to be installed—Figure 5 and 6).

Figure 13 shows the growth of the system flexibility requirement induced by increases of the VRE penetration. First of all, it should be noted that the major reduction of flexible capacity is due to the smoothing effect resulting from enlargement of the forecast-controlled area. Therefore, removing the constraints between market zones not only allows the best use of available balancing production units throughout the country but also reduces the amount of tertiary and secondary reserve that should be held back to balance the system.

In the case of six balancing zones, solar regulation does not significantly reduce the required flexibility, while solar-wind regulation is much more effective and reduces the requirements for flexible thermoelectric capacity by 24–26% at 2030 and 2040. In the case of a single national balancing zone, the benefit of solar/VRE regulation is less than in the six balancing areas, because it has already been greatly reduced by the increase in forecast accuracy.

However, VRE regulation strategy is able to keep the flexibility requirements below the current level eliminating any needs of build new thermoelectric reserve for residual demand/scheduled supply balancing.

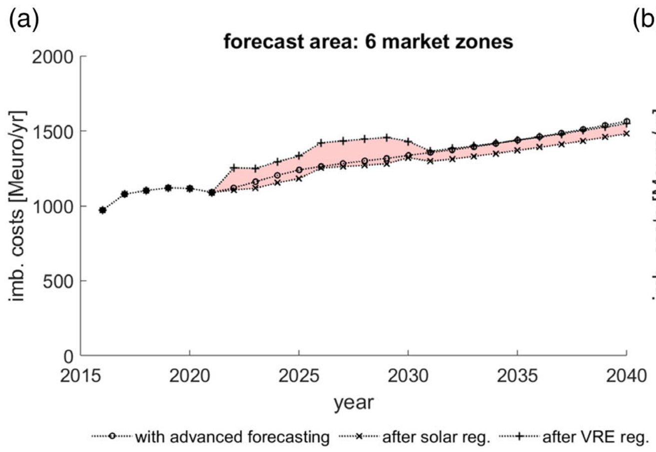

Figure 12. Costs of balancing using our forecast and of balancing using solar/VRE regulation with implicit storage, both a) in the case of the imbalance resulting from the six market zones forecast and b) in the case of a unique national prediction.

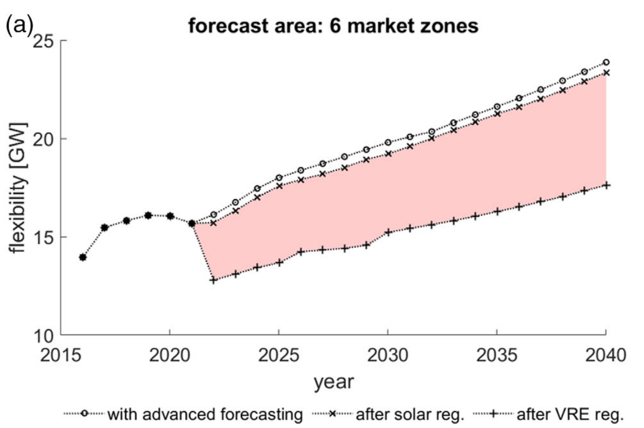

Figure 13. Flexibility requirements for system balancing using our forecast and using solar/VRE regulation with implicit storage, both a) in the case of the imbalance resulting from the six market zones forecast and b) in the case of a unique national netload prediction.

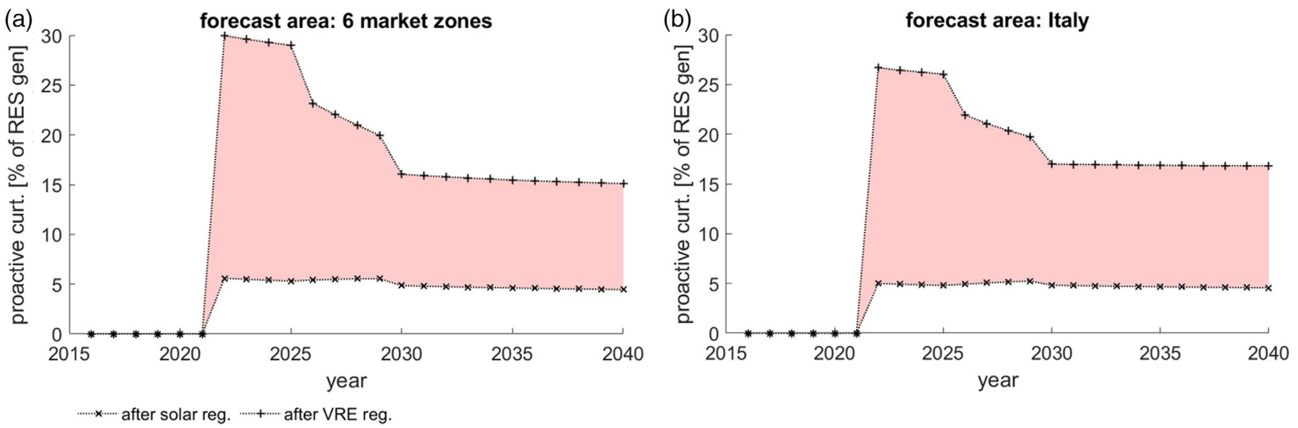

Figure 14. Proactive curtailment needed for upward/downward using solar/VRE regulation with implicit storage, both a) in the case of the imbalance resulting from the six market zones forecast and b) in the case of a unique national prediction.

Figure 14 depicts the VRE proactive curtailment required to reduce the imbalance by solar/VRE regulation with implicit storage both for six market zones forecast footprint and for a unique national forecast-controlled area. The VRE curtailment does not notably depend on the prediction area explaining why the two strategies are much more effective if coupled with grid reinforcement actions. Indeed, in this case, lower imbalance (due to forecast smoothing) and same curtailment and storage injection can only bring to higher solar/VRE regulation performance.

To reduce the imbalance volumes at the levels reported in Figure 11, the production of flexible solar fleet should be reduced around 5% of the total VRE generation, while the production of flexible solar fleet should be curtailed from 27% to 20% before 2030 and curtailed by 17% from 2030 onward. This means that given the NT scenario's target of 55% generation from RES (Figure 4) for 2030, it would be possible to reach 54% if solar regulation is used, but only 51% with VRE regulation. On the other hand, we showed that VRE regulation contains the system flexibility requirement below the current value even at high VRE penetration levels, thereby avoiding the construction of new thermoelectric reserves. In addition, the thermoelectric production units would only be called to provide regulation services for at most the 25% of the current and future imbalance energy, reducing the need fast power ramping, hence extending their lifetime.

7. Summary and Conclusion

In this work, we explained the principle of the VRE imbalance regulation via flexible solar/wind plants, i.e., PV/wind plants (utility scale or medium-size aggregation) equipped with smart inverters, PPC, and BESS. These plants can be remotely controlled (via the PPC) to provide downward regulation by curtailing their generation or upward regulation by injecting additional BESS power. We further described a technique (that we call "implicit" storage) that, through probabilistic underforecast and additional curtailments, enables VRE systems to provide upward regulation even without the need of batteries.

We proposed two different solutions to provides regulation service by flexible VRE plants and implicit storage: 1) the use of a flexible solar fleet with BESS grid night charging and implicit storage to regulate diurnal imbalance and 2) the use of flexible solar/wind fleets as secondary reserve coupled with implicit storage technique.

We tested the effectiveness of these regulatory strategies in Italy both in the current case in which balancing is carried out on each of the Italian market zones and in a future case (planned by the Italian TSO) in which balancing could be carried out on the entire national area thanks to the strengthening of the transmission grid.

We observed that the imbalance volumes reduction achievable through solar/VRE flexible regulation strategies by 2030–2040 amounts to 20–50% with market zones balancing and 27–80% if the balancing is carried out for the entire Italy. The imbalance costs of the two strategies are comparable with the BAU costs both at zonal and national level.

The most effective measure to reduce the system flexibility requirement induced by VRE penetration is the grid reinforcement aimed at removing the capacity transit constraints between the market zones. Importantly, we found that VRE regulation can limit the flexibility requirements of the system to the present value even with a high share of VRE.

Proactive curtailment of the flexible fleet due to solar/VRE regulation amounts to 27–20% of total VRE generation before 2030 and 17% from 2030 onward, both in the zonal and in the national cases. This means that given the NT scenario's target of 55% RES generation for 2030, it would be possible to reach 54% if solar regulation is used but only 51% with VRE regulation. Proactive curtailment is the environmental cost of stabilizing the system using VRE plants, avoiding the construction of new thermoelectric reserves.

In a nutshell, solar regulation converts variable/unprogrammable renewable energy into more predictable but higher residual electrical demand (that can be easily supplied by the existing baseload thermoelectric park). However, VRE regulation is a necessary and inevitable step toward the energy transition because it makes no sense to build new gas turbine generators dedicated to grid balancing and producing less and less baseload energy.

Finally, it is worth noting that the proposed regulatory and business approach has an important long-term implication.

The energy volumes traded on the ancillary services market (MSD) will be gradually reduced in favor of the day-ahead market, and the prices of balancing energy will decrease.

On the other hand, due to the merit order scheme, day-ahead energy prices tend to fall because of the near-zero marginal costs of VRE, but they could also rise incredibly as they are tied to marginal gas prices (renewable plants are currently making disproportionate and unjustified profits). Today it is for all to see that these Day-Ahead market rules are not adequate for high RES penetration.

We think that approaching the energy transition, both the ancillary services market and DA market are bound to disappear, and the energy market's structure must be simplified in favor of a dedicated renewable energy market driven by LCOE prices or a fixed national prices of the renewable energy.

VREs are the only solution for EU energy resilience and cost reduction, but they need to be kept out of current markets and used in a centralized way for common benefits (such as balancing the national grid).

Acknowledgements

M.P. and D.M. thank the financial support from the Horizon 2020 Programme, under Grant Agreement 952957, Trust-PV project. The authors wish to thank IDEAM S.r.l. that provided the NWP data. The authors are also grateful to IEA task 16 for offering a useful discussion space on the topics covered by this research.

Conflict of Interest

The authors declare no conflict of interest

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

energy imbalance, netload forecast, photovoltaic penetration, system flexibility

Received: August 1, 2022
Revised: September 5, 2022
Published online:

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