Renewable Energy 179 (2021) 1694–1705

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

# Imbalance mitigation strategy via flexible PV ancillary services: The Italian case study

Marco Pierro [e, *], Richard Perez [c], Marc Perez [d], David Moser [e], Cristina Cornaro [a, b]

[a] Department of Enterprise Engineering, University of Rome Tor Vergata, Rome, Italy
[b] CHOSE, University of Rome Tor Vergata, Rome, Italy
[c] State University of New York, Albany, United States
[d] Clean Power Research, Napa, CA, United States
[e] Institute for Renewable Energy, EURAC Research, Viale Druso, 1, 39100, Bolzano, Italy

## ARTICLE INFO

*Article history:*
Received 12 March 2021
Received in revised form
8 July 2021
Accepted 16 July 2021
Available online 20 July 2021

*Keywords:*
System flexibility
Photovoltaic penetration
Netload forecast
Energy imbalance

## ABSTRACT

Large share of solar energy imposes a higher system flexibility to resolve the increased demand/supply imbalance due to the inherent intermittency and variability of the resource. In this work, we demonstrate that the additional solar-induced flexibility requirement can be fully provided by a special kind of solar farms, namely flexible PV. These plants are able to provide ancillary services by proactive generation curtailment and storage power injection and they can be managed exactly as the secondary reserve currently used. At the current and future penetration levels, we sized the flexible PV fleet required to reduce the Italian imbalance by 36 % (with respect to its 2016 value) while keeping the curtailment at 6 % of the national PV generation. We show how this result can be achieved at an equal or lower dispatching cost than current cost (depending on the solar share). In addition, we found that a fleet composed of many flexible PV plants with different capacity randomly distributed throughout the country provides an optimal solar regulation performance. Finally, we showed that the effectiveness of the proposed imbalance mitigation strategy depends only slightly on the year-specific load, wind, PV and energy prices profiles used to size the capacity of the flexible fleet.

## 1. Introduction

One of the main barriers to PV system integration is the increasing imbalance between predicted generation and current demand due to the growing share of variable and non-programmable solar generation. To resolve the imbalance, different ancillary services are required depending on the horizon of supply prediction [1–3]: power regulation provided by primary reserve (from second to minute - real time/nowcast-); load following (from minute to hour - now cast/intra-hour forecast-) and unit commitment (hours to days -intra-day/day-ahead forecast) provided by secondary and tertiary reserves.

In 2010, the Industry, Research and Energy Department of the European Parliament stated that “*a major issue for the integration of RE into a power system is the additional imbalance introduced by variable sources … In the absence of a perfect forecast, system balancing requirements and costs are increased by random fluctuations and by forecast errors … Power balancing requirements in large-scale power systems mainly address reserve power in secondary control time scales that is offered on the balancing market*” [4]. The Italian National Energy and Climate plan [5] asserts that with the achievement of the 2030 objectives of 55 % renewable energy generation, “*the high quantity of non-programmable renewable sources will force to keep available a significant portion of thermo-electric generation capacity, in order to guarantee the necessary reserve margins for the safe operation of the system*”. In particular, in Italy solar generation should increase, by 2030, from the current 25 TWh/yr (20 GWp) to 72 TWh/yr (62 GWp[1]) [5]. In Ref. [6] we estimated by 2030 a solar-induced imbalance volume and cost of

---

* Corresponding author.
*E-mail addresses:* marco.pierro@eurac.edu (M. Pierro), rperez@albany.edu (R. Perez), marcp@cleanpower.com (M. Perez), david.moser@eurac.edu (D. Moser), cornaro@uniroma2.it (C. Cornaro).

[1] This PV capacity value is greater than the one reported in the PNIEC since it has been computed using the current PV energy yield and not the energy yield that could be generated by an optimal oriented and well performing PV plant.

https://doi.org/10.1016/j.renene.2021.07.074

**Nomenclature**

| | |
|---|---|
| DSO | Distribution System Operator |
| TSO | Transmission System Operator |
| VRE | Variable Renewable Energy |
| NWP | Numerical Weather Prediction |
| WRF | Weather Research and Forecasting model |
| MOS | Model Output Statistic |
| DAM | Day Ahead Energy Market |
| BEM | Balancing Energy Market |
| BESS | Battery Energy Storage System |
| CAPEX | CAPital EXpenditure |
| OPEX | OPerating EXpense |

7 TWh/yr and 500 M€/yr (considering the current forecast accuracy) that should be added to the current imbalance volume and cost of 17.3 TWh/yr and 1200 M€/yr. To resolve this imbalance, system flexibility (i.e. "the extent to which a power system can modify electricity production or consumption in response to variability, expected or otherwise" [7]) should increase by a more intensive use of current reserve or by the implementation of different measures as, for instance, the built of new fast response generators.

In this work, we show how flexible photovoltaic plants, i.e. PV plants equipped with smart inverters, power controllers and battery energy storage system (BESS), can effectively provide the additional flexibility required by high levels of solar penetration. We prove that the unit commitment services of a suitably dimensioned flexible solar fleet, directly controlled by the Italian TSO (exactly as the current secondary reserve), can even decrease the thermoelectric generation capacity for secondary regulation. Thus, solar can not only solve its own grid integration problems but also help keep the system balanced.

In our previous papers [6,8–11], we demonstrated how flexible plants can operate proactive curtailment (through smart inverters and power controllers) or increase their generation (through battery energy storage) to match the solar forecast as well any kind of load profile.

Here, we recall the imbalance mitigation strategy proposed in Ref. [12] but with two important differences:

- the flexible solar fleet provides regulation services not to correct the Italian PV power forecast errors, but to reduce directly the imbalance of the entire country, so it should be managed exactly like the secondary reserve currently used.
- We sized the flexible fleet to lock the imbalance at a desired value regardless the PV penetration keeping the proactive curtailment as close as possible to a reasonable value (6 % of the national PV generation) without any optimization of the solar regulation costs (as in Ref. [12]).

In addition, we studied the effects of non-uniform spatial and capacity distribution of the flexible fleet and the impact of meteorological conditions and load profiles on the results of the proposed imbalance mitigation strategy. Here we refer to the ancillary service provided by flexible solar PV fleet also as "solar regulation".

This paper is organized as following:

- In section 2, we discussed the novelty of this work with respect to the existing literature;
- In section 3, we briefly introduce the main features of the Italian Imbalance regulatory framework and we explain how it is possible to provide solar imbalance regulation via flexible PV plants;
- In section 4, we describe the methodology followed in our investigation;
- In section 5, we present the data used in this work;
- In section 6, we describe and discuss our results;
- In section 7, summary and conclusion are reported.

## 2. Novelty of the work with respect to the existing literature

The additional energy flexibility requirements discussed in this paper deal with the increased power ramps induced by the variability and intermittency of the VRE generation and with the imbalance due to the increasing uncertainty of net load predictions (where the net load is the difference between demand and VRE production that should be met by programmable generation sources). The first problem is related to the inability of wind/solar plants to generate dispatchable baseload profiles, while the second is related to the lack of full predictability/programmability of these renewables. Both of these challenges can ultimately be resolved by additional thermoelectric generators with suitable response rates able to follow residual load ramps or provide ancillary power and energy services for voltage and frequency regulation.

Ongoing research proposes several complementary measures alternatives to building further conventional generators [2,7,13,14]. Some of them are advanced flexibility solutions, still the subject of energy system simulations and far from being implemented: demand-side management [15] or sector coupling [16]. Other supply-side flexibility solutions have already been tested (see for example the case studies reported in Ref. [7]) and ready to be implemented on large scale: (1) advanced forecasting techniques; (2) grid improvements to remove congestions, provide a better share of renewable and increase forecast accuracy; (3) intensive use of different kind of storage; (4) power curtailment of VRE generation; (5) aggregators to manage virtual power plants.

(#1) As variable renewable energy (VRE) supply depends on meteorological conditions, their generation increases the uncertainty of the net load prediction (i.e. the supply of programmable generators that should be provided to meet the next day's demand). For these reasons, the use of advanced VRE forecasting techniques can improve programmability, increase the accuracy of the generation forecasts, and decrease the demand-supply imbalance and its related costs [12,17–21].

(#2) A well-designed transmission system enables both the full exploitation of the renewable potential avoiding grid congestions and the most efficient use of all the flexible resources available on the territory. Moreover, removing grid bottlenecks enables larger VRE forecast controlled areas and thus increase the prediction accuracy (due to the geographical smoothing of the forecast errors). Therefore, improving the grid infrastructure to remove constrains and increasing transmission capacity will reduce system flexibility requirements as well [12,22–24]. In particular, Müller et. Al [23]. compute (by the European electricity market model) the investment trade-off between transmission grid expansion, storage installation and RES curtailment, concluding that "optimal transmission line expansion is the preferred option in comparison to additional storage facilities".

(#3) It is widely known that for a high share of VRE generation, energy storage is an essential component to improve dispatchability of these resources [8,10,11,25,26] and provide different kind demand/supply services [12,27–30]. In their valuable reviews [1,31], Kondziella and Beaudein provided a comprehensive survey of all types of storage currently on the market and their applications to improve system flexibility.

(#4) VRE curtailment (power limitation) is a consequence of grid constrain, system security or VRE over-generation (when storage is absent or insufficient). As it implies losses in green energy produced at near zero marginal cost, it was considered as to be absolutely avoided. However, with the current wind/solar learning curves many simulations by energy system models indicate that the least cost high RES scenarios should consider a non-neglectable level of VRE curtailment [23,26,32–34]. Jacobsen et al. in their notable work [35], provided a classification of curtailment events in terms of reasons, involuntary, voluntary and rationale. Along this direction, Perez et al. [6,8] demonstrated 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.

Curtailment can also be used to provide grid ancillary services: "*VRE plant output can be curtailed, when necessary, to prevent surplus power in the system or to reduce the rate of (upwards) change of output. 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. Such curtailment or backing down might only be needed for a few hours* per *year (i.e. presenting acceptable costs to the producer), and full flexibility assessments should take account of this option as it may result in the ability of a power system to manage a greater capacity of VRE*"(IEA Guide to the Balancing Challenge [7]). However, while downward regulation services can be easily provided by curtail VRE generation, upward regulation is not an easy task as defining how much VRE plants should be kept unloaded from their rated capacity is not trivial. Authors did not found studies that address this issue while this is one of the main goals of this work.

(#5) An aggregator is a company that control several distributed energy resources (DERs: disperse traditional and RE generators of small and medium size, consumers, prosumers, storage, controllable load as electric vehicles or heat pumps etc.) and interact with the grid/energy markets as a unique system agent. The aggregator's portfolio of DERs acts as a single plant (called "Virtual Power Plants") with capacity comparable to conventional generators. As reported in Ref. [36], aggregators can provide several services depending on their DERs park, among which the delivery of ancillary services to transmission (and potentially distribution) system operators.

Aggregators already started to be used in several countries, some examples could be found in the IRENA report [36].

In order to allow all these flexibility measures to be fully operational and widely used, it is essential to review the current regulatory framework and the rules of the energy markets [35,37,38].

In the Italian case, the main solutions to improve system flexibility prescribed by the government (National Energy Strategy [39]) and planned by the national TSO ("Piano di Sviluppo 2019" [40]) are: (a) remove the grid constrains between the six Italian market zone and market integration; (b) introduction of the "Capacity Market" which should provide a specific remuneration for the thermoelectric plants (CCGT); (c) allow ancillary services from virtual power units (UVAMs – *Unita' Virtuali Abilitate Miste* -) of minimum 1 MW made of storage and production/consumption units with maximum 40 % of their capacity from VRE [41]; (d) improve Pump Hydro Storage capacity and allow battery storage to deliver ancillary services and improve market coupling; (e) Develop new commercial and contractual rules to regulate the relationships between VRE aggregators and TSO dispatchers or end-users.

The novelty of this work is to suggest a supply-side strategy to increase system flexibility based only on solar resources. Indeed, we show how the use of optimally sur-dimensioned flexible PV fleet can effectively provide unit commitment and load following services [2] able to freeze the national imbalance to a desired value regardless the solar share. This strategy embeds all the above mentioned flexibility measures as: the flexible solar capacity was retrieved using an accurate "state of the art" forecast of the whole Italian PV generation (#1 and #2); the flexible fleet make use of storage and proactive curtailment (#3 and #4); the plants composing the fleet can be utility scale flexible farms as well as virtual PV plants managed by solar aggregators (#5). Furthermore, this strategy is simple and straightforward since the TSO would manage the flexible solar fleet exactly as it does with the secondary reserves currently used, i.e., without any change in the regulation procedure.

To allow VRE systems to deliver ancillary services the widespread approach is entrusts the downward regulation to the VRE curtailment/consumers and the upward regulation to the storage/traditional generators (like Banham-Hall et al. [29] and Delfanti et al. in Ref. [30] or the Italian TSO strategy based on UVAMs [41]). In contrast, we provide a solution for upward regulation services by VRE even without the use of storage. We approach this problem from a different perspective than that reported in the IEA Guide to the Balancing Challenge [7] (see above citation). To predict the net load, we propose to intentionally use a solar under-forecast (low quintile forecast) instead of an accurate unbiased prediction (i.e. P50). In this way, all the events during which an accurate net load prediction is underestimated (under generation conditions) so that additional power from storage would be needed to provide upward regulation will most probably turn in to over-forecast events (over generation conditions) that could be corrected by solar curtailment. Therefore, under-forecast/curtailment can replace storage for upward regulation services aka under-forecast/curtailment act as "implicit storage" (as we called in Ref. [11]). We showed that it is possible to reduce the Italian imbalance well below the current value (36 % less) even at a very high solar penetration level solely applying solar under-forecasts and flexible PV proactive curtailment, thereby avoiding the installation of any storage. The price to pay is a 10 % of solar energy curtailment but the gain is an imbalance cost that will remain comparable to the current one when considering the much larger 2040 solar share target.

This is also a win-win strategy since the TSO would reduce its investment in flexibility measures and imbalance regulation costs while the owners of the flexible solar 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 schedule of their production). In case, as in our reference scenario that limit the solar curtailment at 6 %, some storage installation at future level of PV share will be required, the producers will have payback from the TSO also all the storage-related expenses increasing the value of their plants. However, the imbalance costs of our baseline scenario still remain comparable to those of today, as the storage capacity requirements are very limited.

Kondziella et al. states as conclusion of their work [31]: "*Despite an extensive analysis of the technical potential of flexibility options, identified by maximum variation of the residual demand for electricity, there is no evidence that a certain level of storage capacity would be technically required for system stability. Similar to storage options, the balancing of the system could be ensured by VRE curtailment (so-called negative flexibility) and flexible power plants (e.g., gas turbines and positive flexibility) as well*". We find similar conclusions but in our case flexibility is identified with the annual imbalance volumes and the flexible plants are made of photovoltaic farms or virtual solar plants.

Is worth noting that in this work we did not go into detail of the different storage technology as in Cebulla et al. [25] because this is out of our scope but in this study we considered the learning curve of utility scale battery energy storage [42] which, by the way, also Cebulla et al. found to be more suitable for PV applications.

Finally, the results of this study are relevant for the Italian Energy Strategy (TSO/policy makers). First, we demonstrated that photovoltaic can effectively cooperate with UVAMs to provide commitment ancillary services. Secondly, we have shown that there is no need to use the capacity market to incentivize the construction of new CCGT generators (flexibility measure already criticized by the EU) but, at most, this market should promote the use of utility-scale PV plants as flexible generators under the control of the TSO (i.e. as secondary reserve).

## 3. Italian Imbalance regulatory framework and solar regulation services

### 3.1. Balancing energy market

In Italy there is only one TSO (Terna Spa) that manages the whole national transmission grid, ensuring the security and the stability of the system. It constantly monitors the power flows to prevents system outages, avoid congestions, and ensure voltage and frequency stability resolving demand-supply imbalances.

In particular, to keep the grid balanced, Terna issues generation dispatching orders to “Allowed Relevant” Production Units (i.e. flexible power plants with capacity greater than 10 MW allowed to participate in the balancing energy market). In case of negative imbalance (insufficient generation to cover demand), the TSO purchases on balancing market the dispatchable energy needed for upward regulation at a price higher than the day-ahead bulk price (“Prezzo Unico Nazionale”, PUN). In case of positive imbalance, i.e. under-generation, Terna sells the dispatchable energy for downward regulation at lower price than PUN.

The balancing energy market (BEM) is divided into two submarkets: market of the dispatching services (“Mercato dei Servizi di Dispacciamento”, MSD-ex ante) and real-time market (“Mercato del Bilanciamento”, MB).

On the first submarket, Terna purchases/sells with one days in advance the flexible power (reserves) needed to resolve congestions and generation forecast errors:

$$Imb(h) = P_{gen}^{for} - P_{Netload} = P_{Netload}^{for} - P_{Netload} = \left(P_{Load}^{for} - P_{Load}\right) - \left(P_{Wind}^{for} - P_{Wind}\right) - \left(P_{PV}^{for} - P_{PV}\right) \tag{1}$$

where, $Imb$ is the energy imbalance at the hour $h$, $P_{Load}$, $P_{Netload}$ are the load and residual load and $P_{Wind}$, $P_{PV}$ are the wind and solar generation. The superscript “for” means “forecast”.

On the second submarket, Terna purchases/sells in real time the energy required to completely remove the residual imbalance due to unpredictable events, power outages or to reserve estimation errors.

In this work, we only consider the imbalance volume and cost derived by the energy exchanged in the MSD ex-ante, i.e. the imbalance related to the day-ahead net load forecast:

$$Imbalance\ volume = \sum_{h=1}^{Nh} |Imb(h)| \tag{2}$$

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

where, $PUN$, $P_{B\uparrow}$, $P_{B\downarrow}$ are the day-ahead and upward, downward regulation energy prices; $\delta_h$ is a Boolean function that is equal to zero if $Imb(h)$ is positive or is equal to one if $Imb(h)$ is negative; $Nh$ is the number of hours in a considered period (*e.g.* 1 year).

The imbalance energy cost is partially covered by the owners of “Relevant” production units that must pay the TSO in case of incorrect generation scheduling, but the larger share of costs (mainly due to load and distributed VRE forecast errors) are borne by ratepayers, i.e. they are socialized.

It is worth remarking that “Relevant” wind and solar farms are not allowed to participate to the Balancing Market and they can also make a small profit from their imbalance [38] (single pricing rule). In contrast, the imbalance of “Allowed Relevant” production units it is always a cost for the producers.

### 3.2. Solar imbalance regulation via flexible PV plants

In a previous contribution [12], we defined a new kind of PV power plant, namely “flexible” PV plants. These systems are photovoltaic plants equipped with smart inverters, power controllers and battery energy storage systems (BESS). They can be remotely managed to operate proactive curtailment (when generation exceeds the need) as well as to inject additional power from BESS (when more generation is required).

In [12], we showed that flexible PV plants can be cost-effectively adopted to limit the solar-induced imbalance so that the imbalance volume (eq. (2)) can be locked to a desired value independently on PV penetration. In Refs. [6,9–11], we further show that these solar plants can be suitably sized to provide, at costs lower or equal to current costs, a perfectly predictable and programmable generation as well as a full dispatchable, firm generation 24/365.

Here, we investigate the capability of flexible PVs to provide unit commitment ancillary services to directly correct the imbalance (eq. (1)) and not only the PV power forecast errors (as in Ref. [12]). In this case, the flexible solar fleet can be managed by the TSO exactly as the thermoelectric generators currently used for secondary regulations i.e. to meet the netload forecast. In contrast, in our previous approach [12], the TSO would not need to manage the flexible systems to also meet the Italian solar forecasts, complicating the regulation process. Thus, this is a simpler and straightforward imbalance mitigation strategy.

Fig. 1 shows how relevant flexible PVs units can be controlled to reduce the Italian imbalance during 3 days of May 2016. During May 29th, the imbalances are negative (less generation then needed) thus batteries (BESS) inject additional energy into the national transmission grid. Nevertheless, the storage capacity is not enough to remove all the diurnal imbalance. Batteries are then fully recharged during the night using power from the grid. Since the storage state of charge is known after sunset, the recharging energy can be easily programmable during the night so that there is no need to use fast generators dedicated to secondary regulation (reserve). During May 30th, the imbalances are positive (more generation than needed) hence the flexible PVs generation can be proactively curtailed to reduce the imbalance. In this case, there is enough flexible PVs capacity so that the solar downward regulation can completely remove the diurnal imbalances. It is worth remarking that, in case of positive imbalances, the exceeding flexible PVs generation can be not only curtailed but also used to recharge the storage (if necessary). During May 31st, there are still

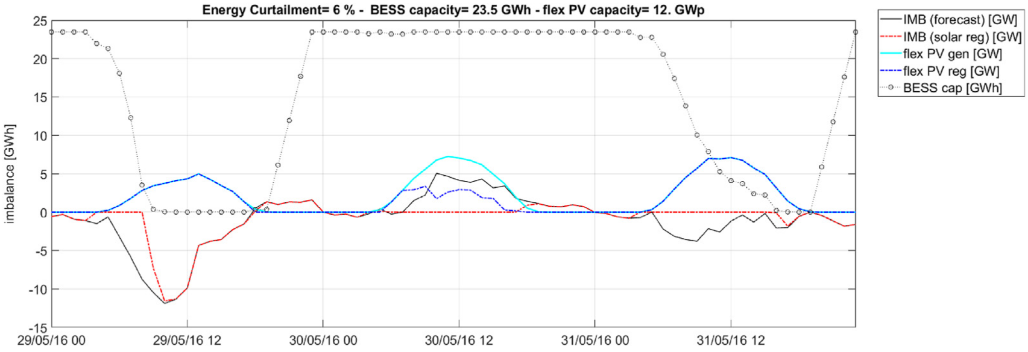

**Fig. 1.** Italian imbalance regulation via 12 GWp/23.5 GWh of flexible PV plants during 3 days in 2016.

negative imbalances, however, in this case, the solar upward regulation provided by the BESS can almost fully resolve the diurnal imbalances.

It is important to stress that, at a given solar penetration, different sizes of flexible fleets (i.e., fleets with different solar and BESS capacities) can provide regulation services that lead to the same reduction in imbalance.

The use of the best PV generation forecast leads to a specific imbalance volume, so that to reduce the imbalance to a desired target value by solar regulation, a suitable flexible solar and storage capacities are required.

The use of a PV generation under-forecast most probably produces netload over-forecast (eq. (1)) hence increase the need of solar downward regulation to resolve the resulting positive imbalance. In this case, to reach the same imbalance target, more solar capacity than storage is required. In this way, BESS costs are reduced but volume and cost of flexible PVs generation curtailment increase.

Therefore, for each PV under-forecast quantile, flexible PV and BESS capacities can be sized to provide the regulation services needed to reach a desired netload imbalance target (residual imbalance). As result, for each PV under-forecast quantile we have a specific solar regulation cost (depending on the amount of solar pro-active curtailment, and on the BESS CAPEX, OPEX and night recharging).

## 4. Methodology

To assess the capability of flexible solar farms to reduce the Italian imbalance volumes at different PV penetration levels, we adopted the following methodology:

1. We sized the flexible PVs so that they can keep the imbalance locked to a desired target value regardless the PV penetration. The target value was arbitrary set to 11 TWh/yr corresponding to a reduction of 36 % of the 2016 imbalance volume (17.3 TWh/yr) [43]. This value has been chosen since it requires the installation of reasonable flexible PV and BESS capacities and leads to feasible solar regulation costs.

We consider the photovoltaic capacity growth scenario from 2016 to 2040 reported in Fig. 2a. It embeds the real capacity values from the statistic reports of the state owned company "Gestore dei Servizi Energetici" (GSE) [44], the solar capacity that should be installed in Italy up to 2030 according to the Integrated Energy and Climate National Plan (PINEC) [5], and the 2030–2040 values reported in Ref. [12].

We further assume that the annual load demand, wind generation, annual insolation and energy prices remain constant over the years, frozen at their 2016 values. Fig. 2b reports the growth of the solar penetration and "unconstrained" curtailment resulting from solar capacity growth scenario and the 2016 hourly load profile. We call "unconstrained" the reactive curtailment that the TSO must necessarily impose when PV generation exceeds the demand. This differs from the proactive curtailment intentionally made to increase solar dispatchability.

In this phase, we initially consider the flexible PV plants uniformly distributed over Italy and assume that they all have the same capacity.

2. For each year, among all the possible flexible PV sizes that lead to the desired imbalance target (resulting from the use of different PV generation under-forecast levels), we chose the solar and BESS capacities that keep proactive curtailment as close as possible to 6 % of the Italian PV generation. In this way, we defined a reference scenario of flexible PV growth. Obviously, the reference scenario is arbitrary and other solutions can be chosen. For instance, as in Ref. [12], one can choose the least expensive scenario, regardless the solar proactive curtailment.
3. We investigate the impact of non-uniform power and spatial distribution of the flexible PV plants on the effectiveness of their solar regulation ancillary services.
4. We further analyze the effect of different solar and wind generation, electric demand and energy prices on the solar regulation capability with respect to the reference scenario (computed using 2016 data)

To compute the imbalance cost we used eq. (3) while to calculate the solar regulation cost we considered that Terna would refund the producers as follows: curtailment and night recharging at PUN price, BESS CAPEX and BESS replacement according to the cost learning curve in Fig. 2c [42], BESS OPEX at 1 % per cycles as in Ref. [8] (that means between 1.7 % and 2.5 % of the total CAPEX depending on the number of equivalent yearly full cycles, coherently with [45,46]). The battery life time (BLT) was set to 15 years and the yearly BESS replacement was considered proportional to the BESS installed capacity by a factor: 1/BLT. It is worth remarking that PV costs (CAPEX and OPEX) are not included in the solar regulation costs since the required flexible solar capacity is only a fraction of the whole PV capacity that have to be installed to meet national and international targets (Fig. 2a). Therefore, we just assumed that a part of the installed utility scale solar plants will be turned into flexible with no additional costs for the owners.

In our approach, flexible PV plants are considered fast secondary reserve hence obligated to provide imbalance ancillary services by TSO automatic power control. Nevertheless, they are relevant plants or relevant virtual production units still not allowed to participate to BEM. In our business model, the owners that accept

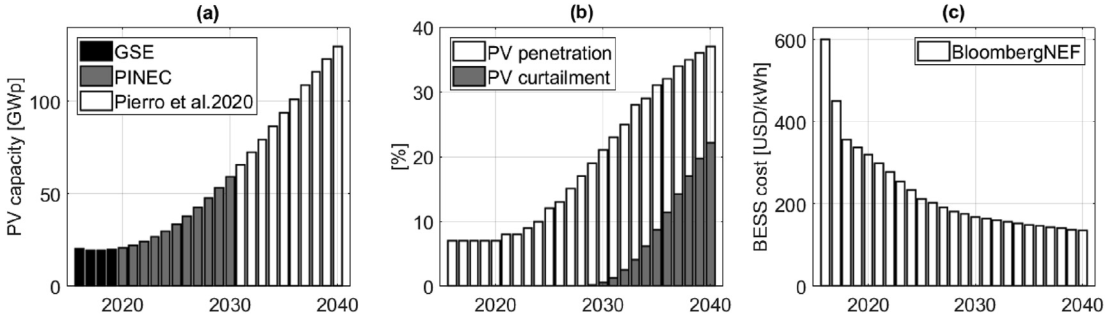

**Fig. 2.** Photovoltaic capacity growth scenario (a); PV penetration and "unconstraint" curtailment scenario (b); Utility scale BESS learning curves inferred from the report "Energy Storage Outlook 2019" of BloombergNEF [42] (c).

to turn their solar plants into flexible assets are not subject to imbalance penalties (as for the "allowed" relevant power units); all the energy produced or dispatched is sold at PUN and they would be refunded of all the costs related to BESS. Therefore, they could improve the value of their facilities with free storage installation.

## 5. Data

We used real Italian hourly load, PV and wind generation data, as well as day-ahead and MSD ex-ante energy prices related to the years 2014–2016 and we assume 2016 as reference year. The data are public and downloadable from the Terna Spa website [47].

The forecast models used to generate the load, wind, PV power predictions were generated by the novel methods described in our previous work [12]. In Refs. [12,24], we demonstrated that these forecasts can be considered at the state of the art level.

## 6. Results

### 6.1. Flexible PV sizing

As explained in section 3.2, at a given solar share, the size of the flexible PV fleet that must provide the ancillary services needed to bring the imbalance to a desired value depends on the level of under-prediction/proactive-curtailment of national solar generation that the TSO has chosen to use.

Fig. 3a shows the flexible PV size required to reduce imbalance to the target value of 11 TWh/yr, according to the under-forecast/curtailment and the 2020/2030/2040 PV penetration levels.

Fig. 3b illustrates the imbalance volumes at the 2020/2030/2040 solar penetration levels and how they can be lowered to 11 TWh/yr by the ancillary services provided by the flexible PV fleet (previously dimensioned on the basis of a specific degree of under-forecast/curtailment - Fig. 3a -). The figure also reports the costs of both residual imbalance and of flexible PV solar regulation. The bars are divided into four parts: the energy provided by the flexible solar fleet for downward/upward adjustment needed to reduce the national imbalance to 11 TWh/yr and its related costs (blue and orange); the energy for downward/upward regulation needed to resolve the residual 11 TWh/yr imbalance that must be provided by other flexible resources and the resulting costs (light blue and pink).

At 2020 PV penetration, for any under-forecast level, the solar generation curtailment strategy is enough to achieve the targeted imbalance volume without the need for BESS, i.e. only downward solar regulation is required.

As expected, the lower the PV forecast quantile, the higher the downward regulation volumes implying higher levels of flexible PV proactive curtailment. Consequently, since downward regulation is much cheaper than upward, the imbalance costs decrease with the under-forecast level.

At 2030/2040 penetrations (21 %/37 %), the installation of BESS depends on the level of applied under-forecast/proactive curtailment. By 2030, a small amount of storage will be needed if proactive curtailment is less than 6 % of the Italian photovoltaic generation. By 2040, BESS will be necessary if proactive curtailment is less than 10 %. It is worth noting that, even at high penetration, the residual imbalance target could be reached with downward regulation only but with a proactive curtailment of 15 %.

It is also important to note from Fig. 3a that the required flexible PV capacity tends to decrease with the under-forecast level. Indeed, the use of a PV under-forecast increases the match between flexible PV generation and positive imbalance events so that there is a more effective solar downward regulation. Therefore, more curtailment but less flexible capacity is required to achieve the target.

Finally, it is worth pointing out that at 2016 solar share, to reduce the imbalance to 11 TWh/yr (using our 50 PV forecast quintile) we would need 3.6 GWp of flexible solar capacity and 7 % of curtailment. If instead we use the flexible PV fleet to correct only the Italian PV generation errors (solar-induced imbalance), as we initially proposed in Ref. [12], we would need 3.7 GWp and 4.4 % of curtailment to bring the imbalance to 12.2 TWh/yr. Therefore, almost the same flexible fleet used for solar regulation brings to different residual imbalance values depending on how it is handled.

This depends on two reasons:

1. Solar forecast errors can also reduce the imbalance of the net-load as they could balance out the forecast errors of load and wind generation, thus limit/remove the solar-induced imbalance could also have a negative impact. For example, Fig. 4 shows the different sources of forecast errors (load, wind and PV) and the resulting imbalance. In this case, clear sky was forecast instead of cloudy causing a negative solar-induced imbalance. However, these negative PV forecast errors have a positive impact on the overall imbalance because they counterbalance the positive load and wind prediction errors.
2. Flexible PV ancillary services reduce the whole imbalance and not only solar forecast errors; thus, the flexible fleet control is more efficient. Indeed, using almost the same flexible capacity (3.6 vs. 3.7 GWp), with the current approach the curtailment is 7 % while in the previous approach [12] the curtailment was 4.4 %.

Therefore, our current imbalance mitigation strategy is not only simpler and straightforward than the one proposed in Ref. [12], since the TSO could manage the flexible PV fleet exactly as it does with automatically controlled secondary reserve, but also more effective.

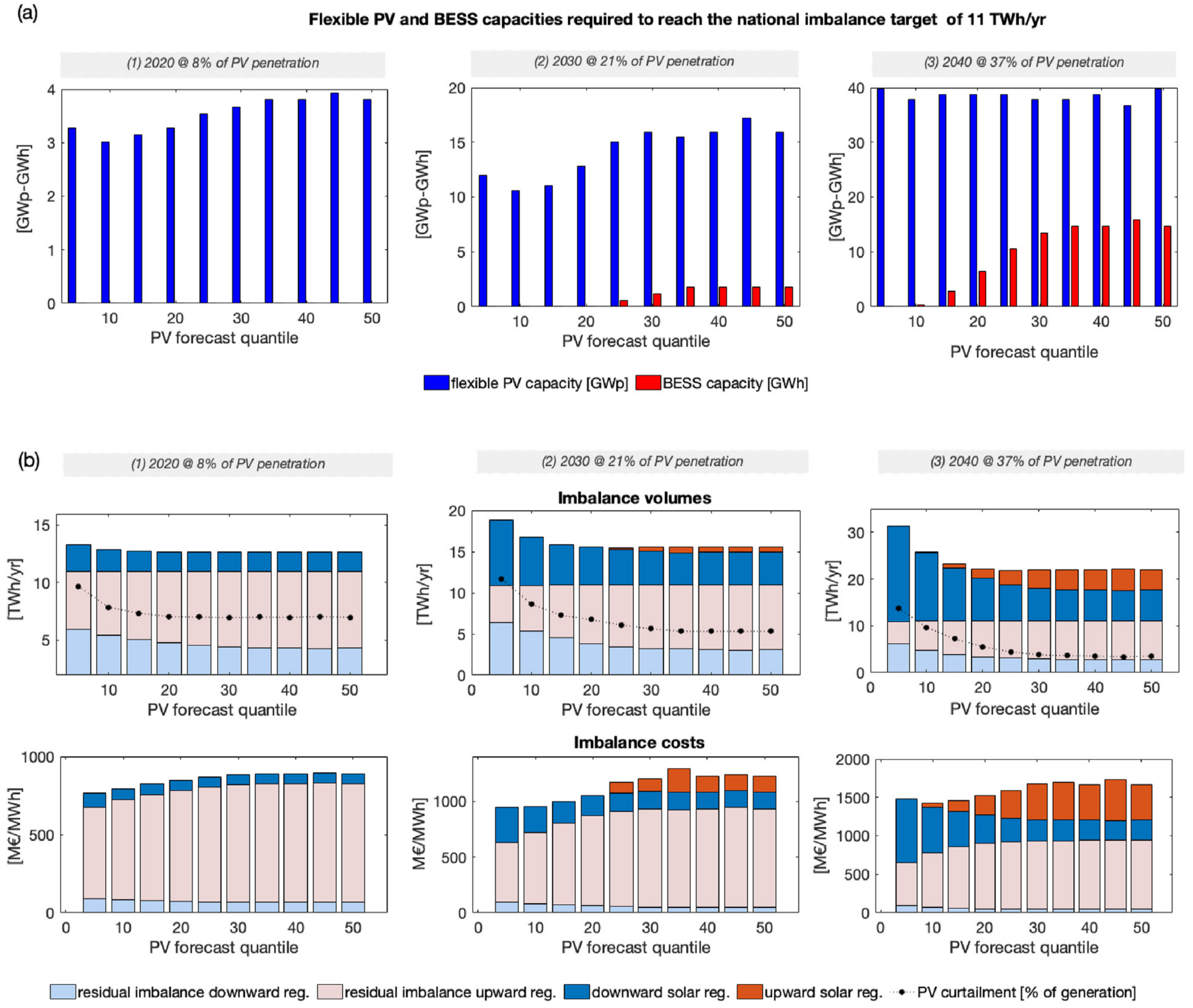

**Fig. 3.** Flexible PV/BESS capacities required to reach the residual imbalance target (11 TWh/yr) according to the PV under-forecast (PV forecast quantile from 5 to 50) at 2020/2030/2040 solar penetration levels (a); volumes/costs of the energy provided by the flexible PV fleet (by solar regulation), flexible PV curtailment (in % of the whole national solar generation) and residual imbalance volumes/costs according to the PV under-forecast at 2020/2030/2040 solar penetration levels (b).

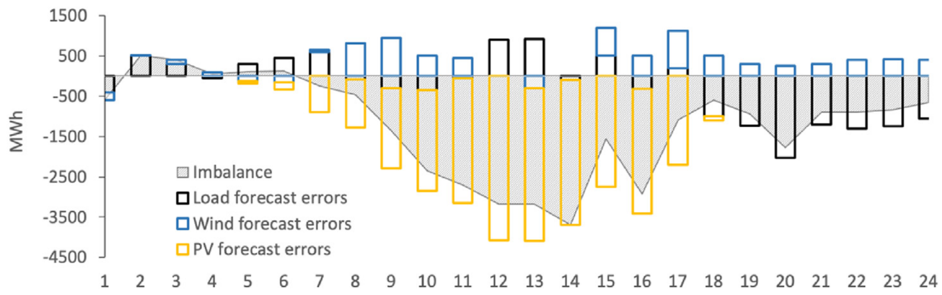

**Fig. 4.** Load, PV and wind day-ahead forecast errors and the resulting systems imbalance during a day in August 2015 in Italy (Source: Terna [48]).

## 6.2. Reference scenario

Among the possible flexible PV capacities (solar and BESS) that lead to a residual imbalance target of 11 TWh/yr, we arbitrary chose as reference scenario the one that keeps the proactive curtailment as close as possible to 6 % of the Italian solar generation.

Fig. 5 shows that to reach the target and limit the proactive curtailment around 6 %, an increasing level of PV under-forecast (forecast quantile) must be applied as PV penetration increases. From the figure, it can be also observed that after 2034 proactive curtailment will be lower than unconstrained curtailment. This means that the solar energy lost for solar regulation is actually less than 6 % since part of the flexible PV production that needs to be proactively curtailed would have been curtailed anyway as solar production exceeds demand.

Finally, Fig. 5 also shows the fraction of the flexible PV generation that should be curtailed for downward regulation. This fraction is obviously much higher than 6 % since the flexible plants should

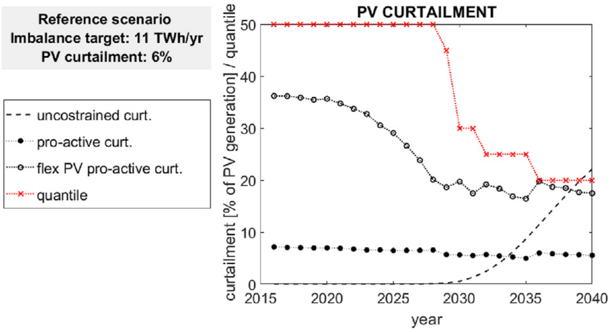

**Fig. 5.** Proactive curtailment in % of Italian PV generation and in % of flexible PV generation, under-forecast levels (quantiles), and unconstrained curtailment.

reduce not only their imbalance but the imbalance of the whole country. Nevertheless, this fraction decreases with time since the required flexible solar capacity grows faster than the PV capacity growth scenario (Fig. 2a).

Fig. 6a displays both the residual imbalance that should be resolved by not solar flexible resources and all the energy components involved in the solar regulation: flexible PV power to BESS, flexible PV curtailment (for downward regulation), BESS power grid injection (for upward regulation) and power from the grid for night BESS recharging. It shows that the ancillary services of suitably dimensioned flexible PV plants can freeze the imbalance to a volume 36.4 % lower than the 2016 imbalance volume (17.3 TWh/yr [49]) regardless of PV penetration (grey bars). Solar regulation can notably reduce also the imbalance obtained by our accurate “state of the art” forecast [12] (line with red dots): 13 % of reduction at 8 % of penetration (2020), 29 % at 21 % of penetration (2030) and 49 % at 37 % (2040).

Fig. 6b illustrates the costs of residual imbalance regulation on the Dispatching Energy Market and the costs of the flexible PV ancillary services according to the proposed business model: PV power to BESS, PV curtailment and BESS night recharging rewarded at PUN energy price, Battery CAPEX (inclusive of BESS annual replacement) and OPEX. It also reports the total costs of balancing the system whether or not solar ancillary services are used (lines with black and red dots). It can be observed that the total imbalance costs using solar regulation and using only our forecast (50th quantile) remains comparable at all the penetration levels and lower than current one until 2033.

Fig. 6c reports the total capacities of the flexible PV systems that should be deployed each year to reach the imbalance target with a solar curtailment as close as possible to 6 %. As previously mentioned, the flexible PV capacity is only a fraction of the current and future installed solar capacity (reported in Fig. 2).

In particular, by 2020 it represents 18.5 % of current 20.6 GWp installed capacity (3.6 GWp), by 2030 it should represent 27 % of the expected 59 GWp that will be installed according to PNIEC [5]. By 2040, it will correspond to 29 % of the 130 GWp that we predict to be installed. The required BESS capacity reaches a maximum of 6.5 GWh by 2040. For this reason, solar regulation costs result affordable. It is worth noting that, at current penetration level, the residual imbalance target could be obtained without the need to install any storage or use any solar under-forecast for the netload prediction; the TSO could achieve this by managing 3.6 GWp of the already installed 4.5 GWp utility scale PV fields (capacity greater than 1 MWp) as flexible plants. Furthermore, the capacity of utility scale solar plants (Jumbo-projects) that is expected to be installed by 2030 is estimated between 25 and 50 GW (source from confidential reports). Thus, part of these new solar plants can be easily managed as flexible plants to provide commitment ancillary services.

Fig. 6d depicts the new solar flexible capacity that should be added each year to obtain the capacity targets reported in Fig. 6c. In 25 years, an average of 1.9 GWp of PV equipped with 0.43 GWh of battery storage should be annually installed or turned into flexible.

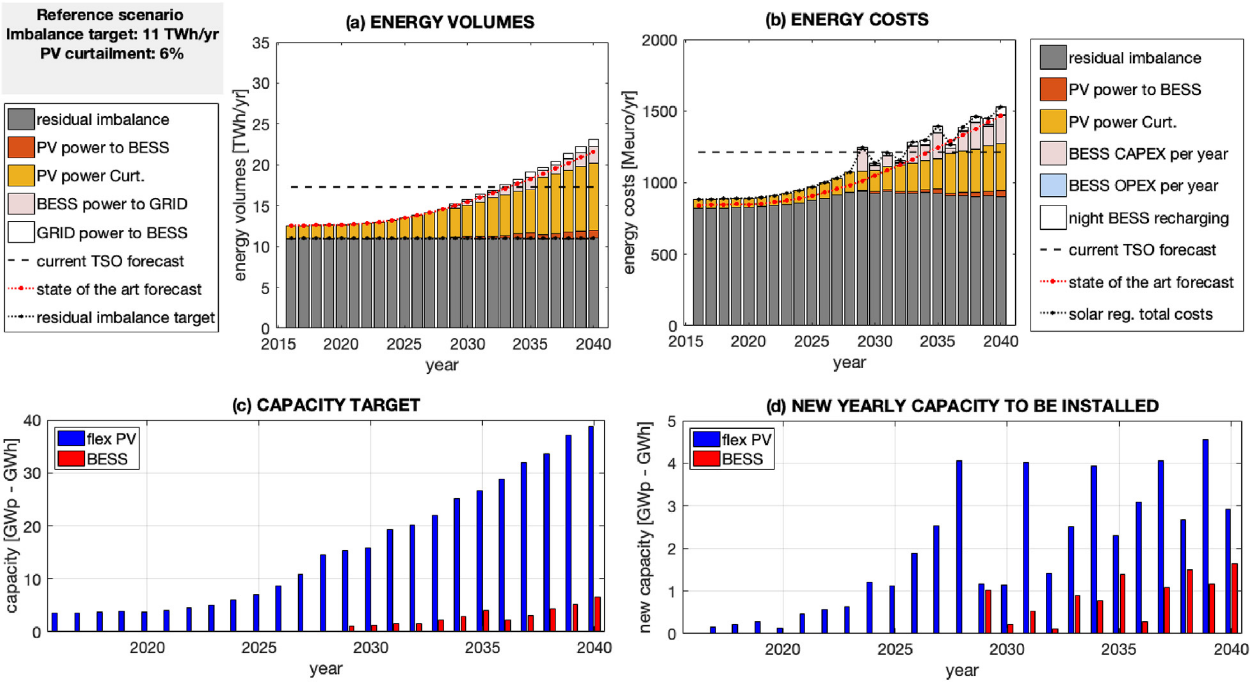

**Fig. 6.** Residual imbalance/solar regulation energy volumes and costs (a and b); flexible PV total capacities (PV and BESS) required to achieve the residual imbalance target with 6 % of proactive curtailment (c); flexible PV capacities that have to be installed to reach the required flexible PV total capacities target (d).

### 6.3. Effect of flexible PV fleet spatial and capacity distribution

We investigated the impact on the solar regulation performance due to a spatial and capacity non-uniform distribution of the flexible solar fleet studying the residual imbalance deviations from the target value of 11 TWh/yr.

Fig. 7a illustrates the residual imbalance obtained by placing all the previously dimensioned flexible plants in a unique location identified by a cell of 12 × 12 km (lines with blue and red dots), the current imbalance (grey dashed line) and the imbalance volume achievable with our “state of the art” forecast (line with grey dots). We choose the sites with the highest and lowest PV yield: 1573 MWh/MWp and 600 MWh/MWp. In the first case, solar regulation produces almost the same imbalance reduction of the reference scenario. Despite what one would have expected, placing all the plants in the location with the highest irradiance, we would not have better solar regulation performance. The reason for this result is that the generation of PV fleet uniformly spatially distributed has an optimal match with imbalance of the whole Italy (that should be reduced) thereby this flexible PV fleet already produces an optimal solar regulation. In the lowest irradiance case, the solar regulation produces a residual imbalance higher than the reference scenario but still lower than the imbalance resulting from our forecast.

Fig. 7c displays the residual imbalance achievable if the flexible PV fleet is uniformly distributed in one of the 110 Italian provinces as well as in one of the six market zones in which the Italy has been divided (grey and blue lines). It shows that the solar regulation performance increases with the size of the area in which the flexible solar fleet is placed. On a single site scale, the maximum residual imbalance is 15.6 TWh/yr, on provinces scale is 13.1 TWh/yr and on market zones scale 11.65 TWh/yr. Also, this result is due to the increasing match between the distributed fleet generation and the Italian imbalance.

Fig. 7c also reports the results (in terms of residual imbalance) of 20 different simulations in which we have placed 400 flexible photovoltaic systems with the same capacity in locations (cells) randomly selected and distributed throughout the country (lines with red dots). It must be remarked that in each location more than one plant can be placed so that also the capacity distribution is non-uniform. For instance, the 4 GWp of flexible capacity needed for solar regulation in 2021, has been divided in 400 relevant flexible plants of 10 MWp each and randomly distributed all over the 1325 cells (covering the whole Italy) so that one cell can contain a random number of plants. Fig. 7c shows that all the 20 simulations have provided a residual imbalance scenario substantially identical to the reference one (line with black dots).

Fig. 7b and d display the costs of solar regulation derived by the different placement of the flexible solar fleet, showing that these costs are only slightly affected by the spatial distribution of the systems.

In [11], concerning the use of flexible plants for firm power forecast (perfect forecast), we achieved similar results. We showed that to reach the perfect predictability we need a decreasing flexible capacity if we place the systems homogeneously distributed in a wide area (NY–ISO regions/controlled area) rather than in only one location per region. Nevertheless, here we add another important result: as long as we have a relevant number of flexible systems spread out over a wide controlled area the exact position and power of each single plant does not matter from a solar regulation point of view, i.e. it is not necessary that the fleet is uniformly distributed neither spatially nor in capacity. However, optimal placement might still be necessary to take into account the transmission grid constrains.

Therefore, the most reasonable and realistic assumption that the flexible fleet is made of many plants with different capacity randomly distributed all over the country provides an optimal solar regulation performance.

### 6.4. Effect of yearly data profiles

Until now we assumed that load, irradiance, wind and energy prices remain the same as per 2016 during all the considered period (2016–2040). This is obviously an over-simplification since the meteorological conditions changes year by year. In addition, the load and energy prices will be surely affected by changes in end-user behaviors, future wide-scale electrification of building, industry and transportation sectors, demand-side management, and energy regulation framework.

To investigate how the effectiveness of the solar regulation could depend on these data profiles, we compute the residual imbalance volumes and costs obtained by the previously

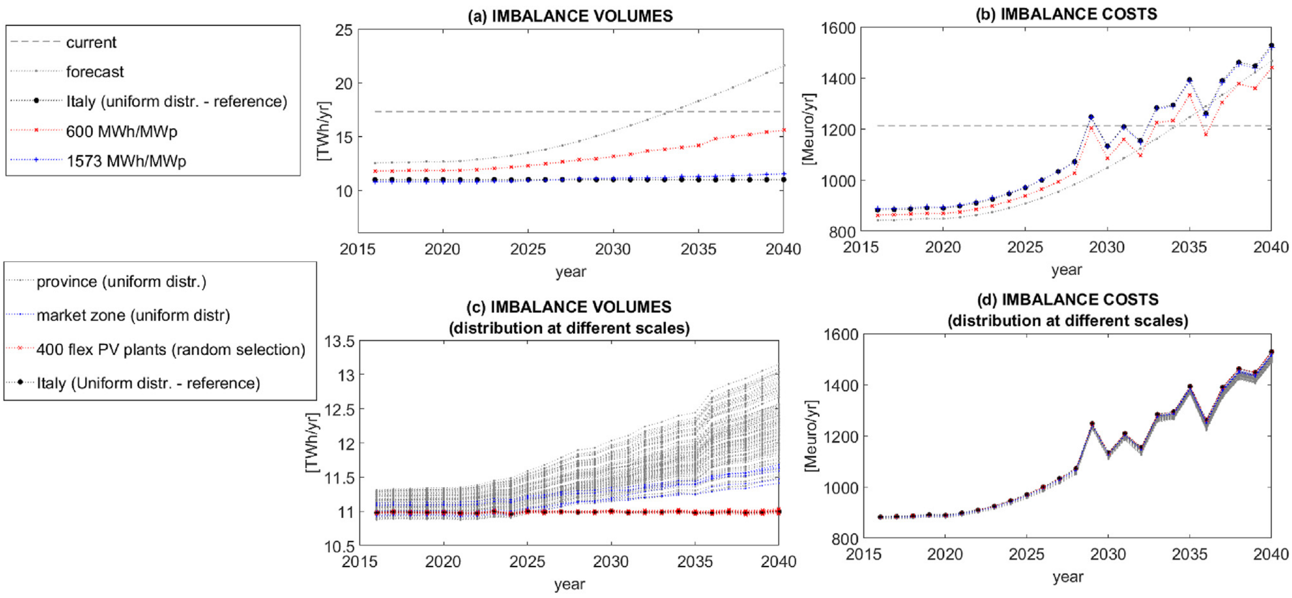

**Fig. 7.** Impact on solar regulation performance of the spatial/capacity distribution of the flexible solar fleet.

dimensioned flexible PV fleet but using the load, irradiance, wind and energy prices profiles related to the years 2014 and 2015.

From Fig. 8 we can observe that the residual imbalance volumes and costs obtained using the 2015 data profiles are substantially the same as those reported in the reference scenario (Fig. 6). The residual imbalance volumes obtained using the 2014 data profiles are instead slightly lower while the residual imbalance costs are lower or equal to the reference scenario only until the year 2035.

These differences mainly depend on the PV forecast errors in the different years. Using 2015 data, the PV imbalance volumes (cumulative forecast absolute errors) are very similar to those resulting from the use of 2016 data. Nevertheless, at high penetration, using the data profiles of 2015, a slightly higher amount of negative solar imbalances appear (under-forecast events) with respect to the reference case (Fig. 9 (b) and (c)). This results in a slightly higher need of downward regulation; indeed the residual imbalance costs decrease while the PV curtailment costs increase (Fig. 8b). This effect is greatly amplified if we use the 2014 data profiles that lead to higher solar forecasting errors mainly due to events under predicted. Consequently, imbalance costs are significantly lower until 2035, but then become higher as the penetration and weight of PV forecasting errors in the netload imbalance increase (Fig. 8a). We must specify that the accuracy of 2014 solar forecasting is lower than in other years because the 2014 irradiance is much less persistent therefore, more difficult to predict [38].

We can conclude that the effectiveness of solar regulation is not directly related to the load, wind, irradiance, and energy prices profiles itself but mainly depends on solar prediction accuracy that can only improve over time. One can still argue that in future the load shape is expected to change much more than between 2014 and 2016. Nevertheless, it should be considered that the load shape is expected to change slowly year by year so that the load imbalance (accuracy of day-ahead load forecast) and its related netload imbalance should not be affected by these changes. In addition, we have shown that at high solar penetration, photovoltaic prediction errors take the lion's share in the imbalances.

## 7. Summary and conclusion

We have shown how optimized solar deployment can effectively solve one of the major problems of the PV grid integration: the growth of the imbalance between demand/supply resulting from the increasingly share of variable and not programmable solar generation. We demonstrated that PV plants equipped by smart inverter, power controller and battery energy storage systems, directly managed by the TSO, can provide ancillary services as well as the combined cycle power generators currently used as secondary reserve. We refer to these so-equipped solar systems as “*flexible PV plants*” as they are capable of providing flexible power for regulation services (i.e. solar regulation). Indeed, they can supply power requirements either by proactive curtailment in case of over generation, or by the storage power injection, in case of under generation.

We sized the flexible PV fleet to provide ancillary services capable of limiting the imbalance of the Italian grid to a desired value regardless of solar energy share, while keeping the curtailment of the national PV generation to a reasonable level.

We studied the benefit of solar regulation at both current and future PV penetration levels. A reference scenario was created using hourly time series of load, PV and wind generation, as well as energy prices for the year 2016 – assuming uniform flexible power distribution all over Italy. We further investigated the impact on solar regulation performance of non-uniform spatial and capacity distribution of the flexible solar fleet as well as of using data profiles for other years.

We demonstrated that this imbalance mitigation strategy is simple and straightforward since the flexible PV fleet can be considered to all intents and purposes as a secondary reserve.

We showed that solar regulation, at 2020 PV share, can reduce the imbalance volume by 36 % with respect to the 2016 value obtained by the current TSO net-load prediction. Solar regulation also provides a significant decrease in the volume of imbalance compared to the imbalance volume resulting from a much more accurate net load forecast (developed by the authors): 13 % by 2020,

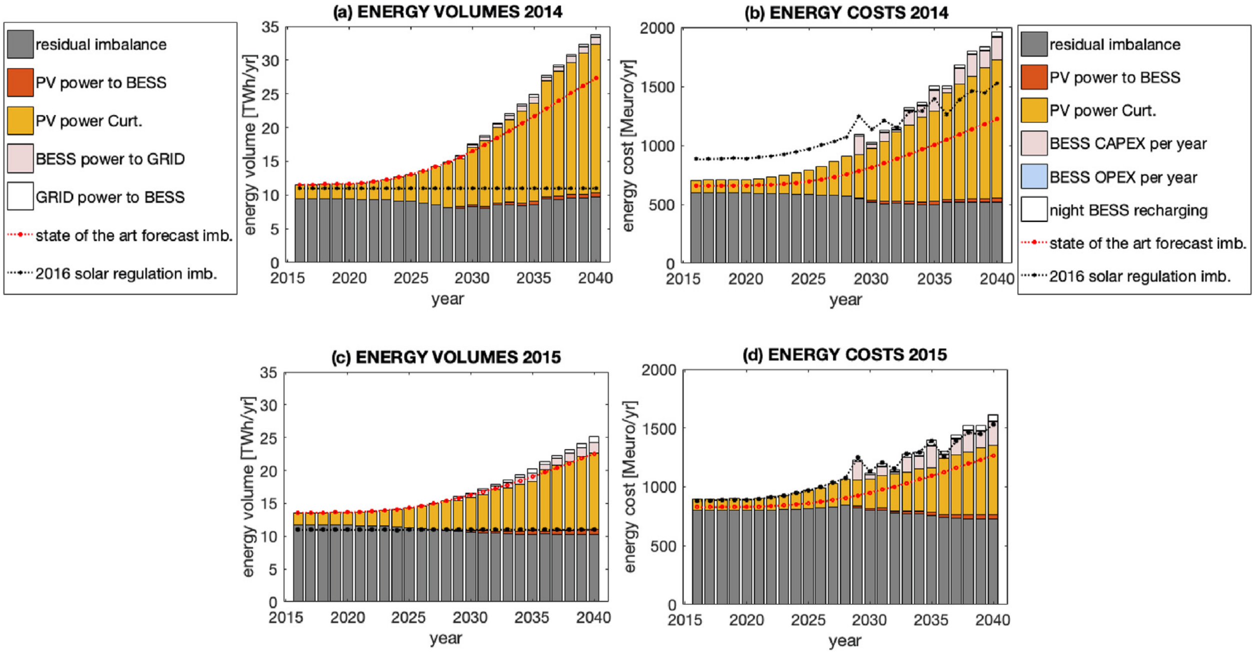

**Fig. 8.** Imbalance volumes and costs obtainable by the solar regulation with the flexible solar capacity dimensioned on the 2016 reference year and the data profiles relate to the years 2014 and 2015.

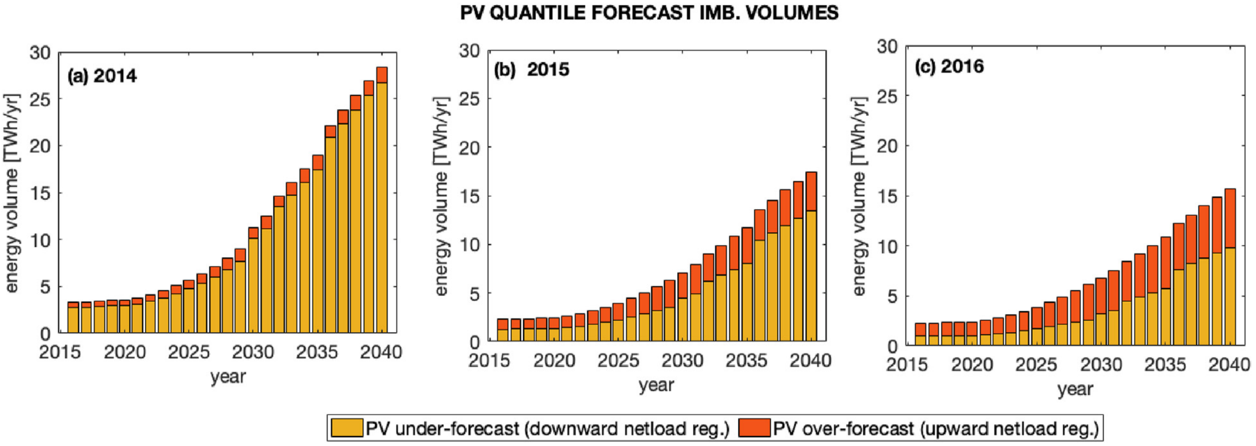

**Fig. 9.** Negative/positive imbalance volumes of the PV quantile forecast (leading to the need of downward/upward regulation) for the years 2014–2016.

-29 % by 2030 and -49 % by 2040. Importantly, the solar regulation costs are less than, or comparable to the costs resulting from PV power forecast uncertainty and the current imbalance regulation procedure based on fast thermoelectric generators.

In addition, we find that a fleet made of multiple flexible PV plants with different capacity randomly distributed over the country provides an optimal solar regulation performance.

Finally, we showed that the effectiveness of the proposed imbalance mitigation strategy only slightly depends on the specific load, wind, PV and energy prices profiles used to size the capacity of the flexible PV fleet but it mainly depends on the PV forecast accuracy that can only improve over time.

## CRediT authorship contribution statement

**Marco Pierro:** Conceptualization, Methodology, Software, Formal analysis, Writing – original draft. **Richard Perez:** Methodology, Supervision, Writing – review & editing. **Marc Perez:** Writing – review & editing. **David Moser:** Results discussion, Supervision, Writing – review & editing. **Cristina Cornaro:** Results discussion, Supervision, Writing – review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgement

Marco Pierro and David Moser thank the financial support from the ERDF Project INTEGRIDS FESR1042 (Province of Südtirol). The authors wish to thank IDEAM S.r.l. that provided the NWP data. We are also grateful to IEA task 16 for offering a useful discussion space on the topics covered by this research. The authors thank the Department of Innovation, Research and University of the Autonomous Province of Bozen/Bolzano for covering the Open Access publication costs.

## References

[1] M. Beaudin, H. Zareipour, A. Schellenberglabe, W. Rosehart, Energy storage for mitigating the variability of renewable electricity sources: an updated review, Energy for Sustainable Development 14 (2010) 302–314.
[2] P.D. Lund, J. Lindgren, J. Mikkola, J. Salpakari, Review of energy system flexibility measures to enable high levels of variable renewable electricity, Renew. Sustain. Energy Rev. 45 (2015) 785–807.
[3] E. Ela, M. Milligan, K. B, Operating Reserves and Variable Operating Reserves and Variable Generation, NREL, 2011.
[4] European parliament - policy department - industry, research and energy [Online]. Available: https://www.europarl.europa.eu/document/activities/cont/201106/20110629ATT22897/20110629ATT22897EN.pdf, 2010.
[5] Pniec, (Piano nazionale integrato per l'Energia e il Clima: inviata la proposta a Bruxelles), 2018.
[6] M. Pierro, R. Perez, M. Perez, M. Prina, D. Moser, C. Cornaro, Italian protocol for massive solar integration: from solar imbalance regulation to firm 24/365 solar generation, Renew. Energy 169 (2021) 425–436.
[7] IEA, Harnessing Variable Renewables: A Guide to the Balancing Challenge, OECD Publishing, Paris, 2011.
[8] M. Perez, R. Perez, K. Rábago, M. Putnam, Overbuilding & curtailment: the cost-effective enablers of firm PV generation, Sol. Energy 180 (2019a) 412–422.
[9] R. Perez, K. Rábago, M. Trahan, L. Rawlings, B. Norris, T. Hoff, M. Putnam, M. Perez, Achieving very high PV penetration – the need for an effective electricity remuneration framework and a central role for grid operators, Energy Pol. 96 (2016) 27–35.
[10] R. Perez, M. Perez, M. Pierro, K.S. Schlemmer j, J. Dise, P. Keelin, M. Grammatico, A. Swierc, J. Ferreira, A. Foster, M. Putnam, T.H. T, Operationally perfect solar power forecasts: a scalable strategy to lowest-cost firm solar power generation, in: 46th IEEE PV Specialists Conference, 2019. Chicago, USA.
[11] R. Perez, M. Perz, M. Schlemmer, J. Dise, f.T. Hof, A. Swierc, P. Keelin, M. Pierro, C. Cornaro, From firm solar power forecasts to firm solar power, Energies 13 (2020) 4489.
[12] M. Pierro, R. Perez, M. Perez, D. Moser, C. Cornaro, Italian protocol for massive solar integration: imbalance mitigation strategies, Renew. Energy 153 (2020) 725–739.
[13] B. Kroposki, B. Johnson, Y. Zhang, V. Gevorgian, P. Denholm, B. Hodge, B. Hannegan, Achieving a 100% renewable grid: operating electric power systems with extremely high levels of variable renewable energy, IEEE Power Energy Mag. (March/April 2017) 61–73.
[14] M. Huber, D. Dimkova, T. Hamacher, Integration of wind and solar power in Europe: assessment of flexibility requirements, Energy 69 (2014) 236–246.
[15] IRENA, Demand-side flexibility for power sector transformation [Online]. Available: https://www.irena.org/publications/2019/Dec/Demand-side-flexibility-for-power-sector-transformation, 2019.
[16] M. G. Prina, G. Manzolini, D. Moser, B. Nastasi and W. Sparber, "Classification and challenges of bottom-up energy system models - a review," Renew. Sustain. Energy Rev. , vol. 129, p. 109917, 202.
[17]] J. Zhang, B. Hodge, S. Lu, H. Hamann, B. Lehman, Baseline and target values for regional and point PV power forecasts: toward improved solar forecasting, Sol. Energy 122 (2015) 804–819.
[18] F. Hamann Hendrik, A Multi-Scale, Multi-Model, Machine-Learning Solar Forecasting Technology, U.S. Department of Energy, 2017.
[19] J. Wu, A. Botterud, A. Mills, Z. Zhou, B. Hodge, M. Heaney, Integrating solar PV (photovoltaics) in utility system operations: analytical framework and Arizona case study, Energy 85 (2015) 1–9.
[20] M. Pierro, M. De Felice, E. Maggioni, A. Perotto, F. Spada, D. Moser, C. Cornaro, Photovoltaic generation forecast for power transmission scheduling: a real case study, Sol. Energy 174 (2018) 976–990.
[21] M. Pierro, M. De Felice, E. Maggioni, A. Perotto, F. Spada, D. Moser, C. Cornaro, Residual load probabilistic forecast for reserve assessment: a real case study, Renew. Energy 149 (2020) 508–522.
[22] A. Kies, B.U. Schyska, L. von Bremen, Curtailment in a highly renewable power system and its effect on capacity factors, Energies 9 (2016) 510.
[23] T. Müller, D. Gunkel, D. Möst, How does renewable curtailment influence the

need of transmission and storage capacities in Europe?, in: 13th European IAEE Conference Düsseldorf, 2013.

[24] IEA PVPS task16, Regional Solar Power Forcasting, 2020.

[25] F. Cebulla, T. Naegler, M. Pohl, Electrical energy storage in highly renewable European energy systems: capacity requirements, spatial distribution, and storage dispatch, J. Energy Storage 14 (2017) 211–223.

[26] M.G. Prina, V. Casalicchio, C. Kaldemeyer, D. Moser, G. Manzolini, A. Wanitschke, W. Sparber, Multi-objective investment optimization for energy system models in high temporal and spatial resolution, Appl. Energy 264 (2020) 114728.

[27] G. Barchi, M. Pierro, D. Moser, Predictive energy control strategy for peak switch and shifting using BESS and PV generation applied to the retail sector, Electronics 8 (2019) 526.

[28] Y. Riffonneau, S. Bacha, F. Barruel, S. Ploix, Optimal power flow management for grid connected PV systems with batteries, EEE Transactions on Sustainable Energy 2 (3) (2011) 309–320.

[29] D. Banham-Hall, G. Taylor, C. Smith, M. Irving, Flow batteries for enhancing wind power integration, IEEE Trans. Power Syst. 27 (3) (2012) 1690–1697.

[30] M. Delfanti, D. Falabretti, M. Merlo, Energy storage for PV power plant dispatching, Renew. Energy 80 (2015) 61–72.

[31] H. Kondziella, T. Bruckner, Flexibility requirements of renewable energy based electricity systems—a review of research results and methodologies, Renew. Sustain. Energy *Rev.* 53 (2016) 10–22.

[32] C. Budischak, D. Sewell, H. Thomson, L. Mach, D. Veron, W. Kempton, Cost-minimized combinations of wind power, solar power and electrochemical storage, powering the grid up to 99.9% of the time, J. Power Sources 225 (2013) 60–74.

[33] W. Powell, A. George, H. Simao, W. Scott, A. Lamont, J. Stewart, SMART: a stochastic multiscale model for the analysis of energy resources, technology, and policy, Inf. J. Comput. 24 (4) (2012) 665–682.

[34] M. Nicolosi, The impact of RES-E policy setting on integration effects - a detailed analysis of capacity expansion and dispatch results, in: Enerday Conference, 2011. Dresden.

[35] K.H. Jacobsen, S. Schröder, Curtailment of renewable generation: economic optimality and incentives, Energy Policy 2012 49 (49) (2012) 663–675.

[36] IRENA, Innovation landscape brief: aggregators [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Feb/IRENA_Innovation_Aggregators_2019.PDF?la=en&amp;hash=EB86C1C86A7649B25050F57799F2C0F609894A01#:~:text=In%20the%20context%20of%20this,provide%20services%20to%20the%20grid, 2019.

[37] M. Joos, I. Saffell, Short-term integration costs of variable renewable energy: wind curtailment and balancing in Britain and Germany, Renew. Sustain. Energy Rev. 86 (2018) 45–65.

[38] M. Pierro, D. Moser, R. Perez, C. Cornaro, The value of PV power forecast and the paradox of the "single pricing" scheme: the Italian case study, Energies 13 (15) (2020) 3945.

[39] SEN, (Strategia Energetica Nazionale), Ministry of Enviroment, 2017.

[40] Terna Spa, Piano di sviluppo 2019, 2019.

[41] Terna Spa (98/2019), Regolamento per la creazione di UVAM [Online]. Available: https://download.terna.it/terna/0000/1117/98.PDF.

[42] BloombergNEF. https://about.bnef.com/blog/energy-storage-investments-boom-battery-costs-halve-next-decade/#:~:text=London%20and%20New%20York%2C%20July,research%20company%20BloombergNEF%20(BNEF), 2019 [Online].

[43] Terna Spa. https://www.terna.it/it-it/sistemaelettrico/dispacciamento/datiesercizio/rapportomensile.aspx/Rapporto_mensile sul sistema elettico_gennaio2017, 2017 [Online].

[44] GSE spa. https://www.gse.it/dati-e-scenari/statistiche ([Online]).

[45] P. Poonpun, W.T. Jewell, Analysis of the cost per kilowatt hour to store electricity, IEEE Trans. Energy Convers. 23 (2) (2008) 529–534.

[46] B. Zakeri, S. Syri, Electrical energy storage systems: a comparative life cycle cost analysis, Renew. Sustain. Energy Rev. 42 (2015) 569–596.

[47] Terna Spa [Online]. Available: https://www.terna.it.

[48] Terna Spa 10/2016, Il mercato per il servizi di dispacciamento (seminario RSE) [Online]. Available: www.rse-web.it/commons/layout/partUploaderView.jsp?CM=FILEVIEW&amp;FILE_TO_UPLOAD=WF_3323_Terna+-+SEMINARIO+RSE_MSD_20161017.pdf%2B%2B%2Bapplications%5Cwebwork%5Csite_rse%5Clocal%5Cdocument%2F003323.Terna+-+SEMINARIO+RSE_MSD_20161017.pdf&amp;TREATASATTACH=yes, 17 October 2016.

[49] Terna Spa [Online]. Available, download.terna.it/terna/0000/0732/38.PDF, 2016.