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Flexible photovoltaic systems for renewable energy integration in Lazio region, Italy

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A R T I C L E I N F O

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A B S T R A C T

Italy is expanding its renewable electricity generation to meet European energy and environmental targets. The aim of this work is to study and implement a strategy to promote a high self-production of non-programmable renewable energies (solar and wind) in the electricity mix of an Italian region (Lazio), to reach the target of 100 % Renewable Energy Source (RES) by 2050 set in the Regional Energy Plan (PER). This can be achieved through the innovative concept of "flexible PV" that has the potential to make solar power generation 24/365. The results showed that by oversizing the photovoltaic in relation to the annual electricity demand and using optimized batteries, 90 % of the electricity demand of the Lazio region can be satisfied by photovoltaic and the remaining 10 % by hydro and wind power. To reach this target, Lazio would need to install 34.73 GWp of photovoltaic capacity and 42.34 GWh of batteries at an optimum cost of 92.21 €/MWh (costs estimated at 2050). In addition, the integration of wind energy into the grid was studied to reduce the photovoltaic capacity.

1. Introduction

The continuous supply of electricity 24/365, a crucial requirement for any power grid, is predominantly met through the combined use of thermal generation (predominantly reliant on fossil fuels), nuclear power (which, it should be noted, is not an available source in Italy), and hydropower. This latter source, however, is contingent upon the availability of water, which can be compromised in drought conditions. Collectively, these power generation methodologies are referenced under the umbrella term of "firm power generation" a term that signifies their reliability in continuous power provision.

The disparate temporal responses of these resources necessitate a judicious blend in their deployment across power grids. For instance, nuclear power and large-scale hydroelectric power are employed to maintain long-term baseloads due to their consistent output. Coal, with its capacity for medium-term supply, forms another integral part of the mix, while natural gas and dispatchable hydroelectric power are relied upon for their rapid response capabilities.

In 2022, Italy's energy mix, according to Terna, the national Transmission System Operator (TSO), was constituted by 70.2 % thermal generation, 10.7 % hydropower, 9.8 % photovoltaic energy, 7.2 % wind energy, and a modest 2.1 % from geothermal sources.

RES, such as wind and solar power, hold tremendous potential to supplant traditional and environmentally polluting generation techniques. However, their applicability as firm power sources are currently limited. Their inherent intermittency and variability, coupled with their inability to provide a steady, on-demand supply of power, restricts their usage predominantly at the margin of centralized power generation.

To replace traditional power generation methods, Variable Renewable Energy (VRE) sources need to evolve from their current position at the margin of a core of dispatchable generation to a grid-dominant position. Intermittent Renewable Energy (RE) requires 24/365 firm power availability as a prerequisite.

Two salient challenges must be addressed to facilitate large-scale VRE adoption:

- The output from VRE sources must match with the load profile.
- Forecasting uncertainties associated with VRE output need to be minimized.

Effectively tackling these challenges necessitates an array of strategies and enabling technologies to instigate the required transformation:

1. Energy storage is paramount in ensuring a stable electricity supply, absorbing surplus VRE generation and releasing it during periods of

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Nomenclature

BESS	Battery Energy Storage Systems
CAPEX	Capital Expenditure
ERAA	European Resource Adequacy Assessment
GTI	Global Tilted Irradiance
LCOE	Levelized Cost of Energy
MISO	Midcontinent Independent System Operator
NDY	Number of daily electric demand to be stored
NREL	National Renewable Energy Laboratory
OVS	Oversize
P	Power
Pn	Nominal Power
PPC	Plant Power Controllers
PER	Regional Energy Plan
PEIROCOM	Pan-European Intermittent Renewable Overbuilding and Curtailment Optimization Model
PNIEC	Integrated National Plan for Energy and Climate
PTE	Ecological Transition Plan
PUN	National Unique Price
PV	Photovoltaic
RE	Renewable Energy
RES	Renewable Energy Source
SAPM	Sandia Array Performance Model
SOC	State of Charge
SP	Self-production
SPt	Self-production threshold
TSO	Transmission System Operator
VRE	Variable Renewable Energy

VRE generation deficit. This strategy is of utmost significance, and while the following strategies can mitigate the necessity for storage, they cannot obviate it entirely.
2. An optimized combination of different VRE sources, such as solar, wind, and hydro, can contribute to a more balanced and reliable energy output.
3. Flexibility in demand can be realized either through customer demand response or by intermittently restraining thermal generation on the supply side, thereby modulating the demand perceived by VRE sources.
4. Geographical dispersion of VRE sources can serve to mitigate their inherent variability, providing a more consistent and predictable output, and increase the RE availability all over the region.

Based on the above four strategies, it is therefore possible to create "firm generation" from renewable sources. However, for this to be economically attractive, the total cost of the energy generated must be lower than that of fossil sources.

Scientific community acknowledges that the most economical approach to transform intermittent renewable sources into firm power generators involves optimally integrating renewable resources with differing daily and seasonal availabilities and incorporating implicit storage strategies. This latter notion involves overbuilding and proactive curtailment to maintain the requirements for energy storage at economically viable levels (Perez et al., 2021a; O'Shaughnessy et al., 2019).

Overbuilding refers to a condition where renewable energy production exceeds the demand required to meet the load on an annual energy basis. This overbuilt resource is dynamically curtailed in instances of surplus VRE production, that is, when production surpasses demand and storage reserves reach full capacity. For deriving optimal configurations, contemporaneous multi-year hourly (or finer) time series are necessitated for both electricity demand and VRE generation.

Taking these foundational premises into account, we have elected to apply the concept of "firm generation" to renewable resources in Lazio, one of Italy's 20 regions. This decision is motivated by the growing interest in renewable energies in Italy, driven by the objective of meeting the energy and environmental targets outlined by the European Community.

In pursuit of these objectives, the Italian government has formulated the Ecological Transition Plan (PTE) (PTE, 2023), which articulates five overarching goals:

1. Achieving climate neutrality.
2. Decreasing pollution.
3. Adapting to climate change.
4. Restoring biodiversity and ecosystems.
5. Transitioning to a circular economy and bioeconomy.

Based on PTE, the Integrated National Plan for Energy and Climate (PNIEC) (PNIEC, 2023) was developed, from which each individual region developed its own Regional Energy Plan (PER Lazio 2022) (PER, 2023).

Several recent studies have explored innovative approaches to curtailment of variable renewable energy (VRE) output to achieve firm photovoltaic (PV) generation (Boland, 2023; van Eldik and van Sark, 2023). These approaches generally emphasize proactive dynamic curtailment, strategic overbuilding of PV generation, and hybridization with other renewable sources to ensure cost-effectiveness and high penetration of renewable energy. The integration of PV and wind power, alongside the use of storage solutions, are key strategies in these efforts. Collectively, these studies highlight the potential for renewable energy to meet growing electricity demands while remaining economically viable. In this framework Perez et al. (2019) (Perez et al., 2019a) demonstrated the benefits of dynamic curtailment and strategic overbuilding of PV in Minnesota, showing that high PV and wind power penetration can be cost-effective. In a second work, Perez et al. (2019) (Perez, 2020) concluded that 100 % renewable generation could be economically viable in the MISO region by 2050, emphasizing the cost benefits of overbuilding and hybridizing wind and PV. Remund et al. (2020) (Remund et al., 2022) found that in Switzerland, an optimal mix of PV, batteries, and flexible hydropower could meet rising electricity demands and replace nuclear energy economically.

In parallel, recent research has underscored the importance of accurate solar forecasts and optimal storage systems in improving firm PV generation (Perez et al., 2019a). These studies generally explore methods for utilizing short-term solar forecasts, optimizing storage solutions, and implementing flexible solar systems to enhance the reliability and cost-effectiveness of solar power. The integration of these strategies aims to achieve high solar penetration and reduce supply-demand imbalances, ultimately contributing to more stable and economically viable PV generation. On this regard, Perez et al. (2020) demonstrated that overbuilt solar power plants, when combined with short-term solar forecasts and optimal storage systems, can achieve extremely high solar penetration at costs comparable to current wholesale prices. Moreover, Pierro et al. (2020a) focused on 24×365 fixed solar power by reducing supply-demand imbalances using flexible solar systems with smart inverters and storage, showing that remote control of these systems can significantly reduce forecast errors and solar-induced imbalances. Finally, Perez et al. (2019a) introduced the concept of a perfect forecast, presenting it as both a forecast and a strategic tool for integrating more solar power into grids with minimal operational costs. These studies collectively provide a robust framework for enhancing solar power generation and regulation. They highlight the critical role of accurate forecasting and optimized storage in achieving reliable and economically viable firm renewable power generation.

Recent research has emphasized the economic viability, cost-effectiveness, and the role of flexibility in firm photovoltaic (PV) generation. These studies generally focus on strategies such as overbuilding VRE systems, proactive curtailment, dynamic curtailment strategies, and enhancing system flexibility through advanced forecasting and grid improvements. Collectively, these approaches aim to reduce imbalances, optimize the cost of solar control services, and ensure a smooth transition to predictable and firm renewable power generation.

Pierro et al. (2021a) presented a cost-effective strategy for Italy to transition to renewables by 2060, highlighting the importance of firm solar and wind generation through overbuilding VRE systems and proactive curtailment. Perez et al. (2021b) compared dynamic and inverter-limited curtailment strategies, finding dynamic curtailment to be more cost-effective for converting intermittent PV and wind resources into firm energy. Similarly, Pierro et al. (2021b) examined the potential of flexible solar systems for ancillary services, demonstrating that effective solar regulation can significantly reduce imbalances, particularly when solar forecasts are accurate. Pierro et al. (2020b) investigated the economic impact of PV forecast accuracy under the Italian "single pricing" system, revealing a paradox where poorer forecasts are financially rewarded, thereby stressing the need for market rule adjustments. Lastly, Pierro et al. (2022) developed a method to enhance system flexibility by integrating advanced solar/wind forecasting with national transmission grid improvements, showing significant potential to reduce imbalances and improve flexibility.

Boland (2023); van Eldik and van Sark (2023); Perez et al., (2019a); Perez (2020); Remund et al., (2022); Perez et al., (2020); Pierro et al., (2020a); Perez et al., (2019a); Pierro et al., (2021a); Perez et al., (2021b); Pierro et al. (2021b, 2020b, 2022); Perez et al., (2019b) These studies introduce several novel aspects that significantly differ from existing literature on renewable energy production. Here, we provide a comprehensive methodology for calculating electricity generation costs, detailing the optimization of PV and storage capacity. Our approach minimizes storage requirements through strategic PV oversizing, reducing reliance on storage systems and improving battery performance in terms of state of charge and cycling. We investigate various levels of flexible PV self-generation rather than focusing solely on 100 % firm power generation. Our analysis demonstrates that flexible PV can meet 50 %, 70 %, and 90 % of energy demand at competitive costs - below €100/MWh by 2025, 2030, and 2050, respectively. This flexibility offers a more realistic and economically viable way to integrate renewables into the grid.

Additionally, we provide a detailed explanation of the optimization process and key parameters used to calculate the LCOE. Our transparent breakdown of factors influencing LCOE and the impact of different variables on total energy generation costs is unique to our study, enhancing the understanding of the economic feasibility of renewable energy strategies.

By applying our methods to the Lazio region of Italy, we demonstrate the practical applicability and relevance of our work, ensuring that the proposed solutions are feasible and effective in practice.

2. PER LAZIO 2022

PER Lazio 2022 reports the regional electricity balance for the last decade (2009–2019), this paper considers the latest available data for 2019. Moreover, PER sets the goal to be achieved in 2050.

The electricity demand of the Lazio region for 2019 was about 23059 GWh, of which 46 % is electricity consumption by the tertiary sector, 29 % by households, 20 % by industry, 3 % by railways and 2 % by agriculture.

Net regional electricity generation in 2019 was approximately 14678.3 GWh, with 80.4 % of this value coming from thermoelectric plants, 11.5 % from photovoltaics, 7.1 % from hydropower and 1 % from wind power.

The gross installed electricity capacity in Lazio is about 7.709 GW, of which 75.8 % is accounted for by power plants from fossil sources and the remaining 24.2 % by renewable sources.

Table 1 shows the number of plants and electricity production in Lazio, broken down by source, for the year 2019.

The PTE sets a new national target for reducing climate-damaging emissions by 2030. The plan therefore points to the need to further reduce primary energy compared to what is already foreseen in the PNIEC: primary energy reductions should increase from 43 % to 45 % (compared to the baseline scenario of the European Primes 2007) and be achieved in the sectors with the greatest potential for energy savings, such as households and transport. Electricity generation must be phased out of coal combustion by 2025 and 72 % from renewable sources by 2030 to reach a level of 95–100 % in 2050.

In accordance with the provisions of PTE and PNIEC, Lazio has set out in the PER to increase the regional share of electricity from renewable sources to 55 % by 2030 and 100 % by 2050.

In this paper, the authors will explore the possibility of achieving these goals using photovoltaics as a renewable resource available throughout the territory.

This choice is dictated by the limited availability of other renewable energy sources in the region (hydro accounts for 7 % of electricity generation and wind 1 %). Moreover, the total electricity demand of the Lazio region in 2019 was 23059 GWh, with hydro and wind together accounting for 8.1 % of the total demand.

The possibility of creating an energy mix of RES (mainly photovoltaic and wind imports) and the impact of this source mix on energy costs and capacity to be installed will also be analyzed. The target for photovoltaics is set at 90 % of annual electricity demand, to be met by hydro and wind power for the last 10 %.

3. Materials and methods

The primary objective of this paper is to optimize the installation of PV systems and BESS to efficiently meet the energy demand of the Lazio region while simultaneously minimizing the economic costs (LCOE) associated with PV and battery installations. By carefully assessing the required amount of PV oversizing (OVS) and BESS capacity, the aim is to achieve a system configuration that maximizes self-production (SP) while ensuring a reliable and uninterrupted energy supply throughout the year.

Through the utilization of an optimization procedure, the study seeks to identify the optimal combination of PV and BESS capacities that not only fulfills the energy load requirements but also reduces the overall costs associated with the installations. This research aims to provide valuable insights and recommendations for policymakers, energy planners, and stakeholders involved in the implementation of flexible photovoltaic generation systems, enabling them to make informed decisions based on the trade-off between energy load fulfillment and economic feasibility.

The strategy employed in this study aims to transform PV generation into a reliable and cost-effective energy source, operational 24/365. As

Table 1
Electricity production and installed power by sources in Lazio in 2019 from (PER, 2023).

	Number	Installed Power		Energy Produced	
		(MW)	(%)	(GWh)	(%)
Hydro Energy	100	411.2	5.3	1048.2	7.1
Wind Energy	68	71.3	0.9	147.4	1.0
Solar Energy	58775	1385.3	18.0	1692.3	11.5
Geothermal Energy	0	0	0.0	0	0.0
Total RE	59063	2040.4	24.2	2887.9	19.6
Total (Fossil)	138	5842.0	75.8	11790.4	80.3
Total (RE + Fossil)	59201	7709.8	100	14678.3	100

highlighted in the introduction, this approach involves oversizing the PV system to minimize the required battery capacity. By doing so, the surplus solar power generated during peak production periods can be used to meet the electricity demand during periods of low solar irradiation using the available storage. However, since the oversupply of electricity cannot be dispatched and monetized, it becomes essential to optimize the capacities of both the PV system (in terms of oversizing) and the BESS to minimize costs.

This section is divided into three parts. The first part describes the concept of firm PV power generation, the second part describes the optimization process and the third the input data of the simulation.

3.1. Firm PV power generation

The strategy is based on a gradual increase in the utilization of flexible photovoltaic and wind power systems. These systems consist of PV plants equipped with cost-optimized BESS, along with smart inverters and power plant controllers that enable dynamic and proactive power curtailment. Despite being counter-intuitive and contrary to current perceptions, proactive power reduction is the crucial element in low-cost and reliable PV generation strategy, as described in Perez et al. (2019a) and Budischak et al. (2013). This strategy suggests that economically optimal firm power generation, in addition to optimizing wind and solar resources (Heide et al., 2010), should deliberately incorporate proactive power curtailment and effectively anticipate power reductions imposed by transmission constraints, as demonstrated in Kies et al. (2016). By optimizing both storage and power curtailment, the injected photovoltaic generation into the grid can be shaped to closely match the predicted output profile, thus eliminating the impact of solar forecast errors. Furthermore, it can subsequently align with the entire TSO load profile, thereby efficiently displacing conventional generation.

3.2. Optimization process

The optimization procedure employed in this study adopts an exhaustive search approach, systematically exploring the entire solution space to identify the optimal configuration of PV and BESS capacity. This method entails a comprehensive evaluation of all possible combinations of PV oversize (OVS) and BESS values within predefined intervals. By traversing this solution space, the algorithm systematically examines the full spectrum of potential configurations, allowing for a thorough analysis of the trade-offs between OVS and BESS capacity.

Through this methodological approach (namely “brute force optimization”), the algorithm starts by iteratively varying the OVS values from the minimum to the maximum, while simultaneously adjusting the BESS values from the maximum to the minimum. Each combination of OVS and BESS is carefully assessed reach the required value of self-production (SP), i.e., the ratio of electricity produced by flexible PV systems and the electricity demand in the Lazio region (net of a predefined amount of imported wind power from the southern zone).

By exploring the entire solution space, brute-force optimization identifies the minimum economic costs (LCOEs) of PV and battery systems (associated with a given SP), ensuring that no potential configuration of PV OVS and storage capacity is overlooked.

LCOE is calculated according to the following equation:

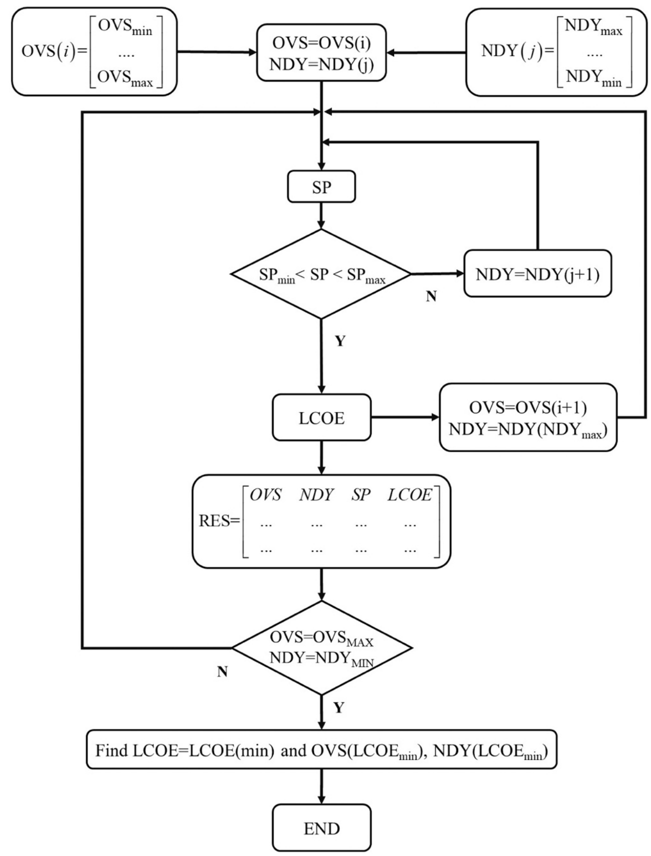

Fig. 1. Block diagram of the minimization process.

where En_{PV2L}, En_{BESS2L}, $En_{res-load}$ are the PV energy self-consumed, the energy delivered by storage and the residual demand that should be purchased from other dispatchable generators at the price energy ($price_{En}$) and En_{load} is the energy demand.

$LCOE_{firmPV}$ and $LCOS_{firmPV}$ are the levelized cost of PV and storage considering only the PV firm generation (i.e., the energy used to meet the demand). $En_{wind-imp}$ and $price_{wind-imp}$ are respectively the wind energy imported and the wind price.

The production cost of PV $\left(LCOE_{firmPV}\right)$ was calculated as in Veronese et al. (2021) and the cost of energy delivered by storage $\left(LCOS_{flexPV}\right)$ was calculated using the detailed procedure developed in Schmidt et al. (2019) that takes into account how the battery is actually used (time degradation and fully equivalent cycles degradation) and the resulting variable O&M expenses.

In this work, for ease of understanding, battery capacity is expressed as "number of daily electric demand to be stored" (NDY). It means the number of consecutive days for which the system can operate solely with the power stored in the batteries, without relying on external energy sources. In other words, it quantifies the system’s ability to sustain the electricity demand of the Lazio region using the stored energy during periods of low solar irradiation or limited renewable energy generation. For instance, if the NDY value is set to 5, it means that the system can sustain the electricity demand for five consecutive days by relying solely

$$LCOE = \frac{\left[En_{PV2L} \cdot LCOE_{firmPV} + En_{BESS2L} \cdot LCOS_{firmPV} + En_{wind-imp} \cdot price_{wind-imp} + En_{res-load} \cdot price_{En}\right]}{En_{load}} \quad (1)$$

on the stored energy in the batteries, without the need for external power inputs. This parameter plays a vital role in assessing the resilience and autonomy of the system, enabling it to operate independently during extended periods of low solar energy availability or grid outages.

By incorporating NDY into the optimization process, the algorithm evaluates various combinations of NDY and OVS to identify the most efficient and cost-effective configuration that meets the energy load requirements while ensuring reliable power supply during periods of limited renewable energy generation. This consideration of NDY allows for a comprehensive analysis of the system's capacity to handle prolonged energy demands independently, offering valuable insights for designing sustainable and resilient photovoltaic generation systems.

As depicted in Fig. 1, the optimization algorithm performs a search for optimal values of NDY and OVS in a countercurrent manner. It scans through the range of OVS values, starting from the minimum value and progressing towards the maximum in the interval from 1 to 10 with steps of 0.05. While simultaneously exploring the range of NDY values in the opposite direction (from maximum to minimum), namely from 90 to 0 with a step of 0.05 (firsts three blocks of the Fig. 1).

For each OVS(i) and NDY(j) value pair, the model calculates the corresponding self-production (SP) value. If the obtained SP value falls within the specified SP threshold (SPt) $\pm$ 0.5, the model proceeds to evaluate the LCOE, according to Eq. (1).

However, if the SP value is outside the SP threshold range, indicating that the self-production is significantly above or below the desired target, we employ an iterative approach. In such cases, we decrease the NDY value to adjust the system's energy storage capacity. By iteratively modifying the NDY value, we aim to find a configuration that satisfies the SP threshold (second and third block of the Fig. 1).

When the SP value falls within the SP threshold range, we store the corresponding values of OVS, NDY, SP, and LCOE and other secondary information.

These values are then recorded for further analysis and comparison described in the results section. Subsequently, we restart the iteration process with the next OVS value, repeating the steps mentioned above. (fourth, fifth and sixth blocks in Fig. 1) This iterative approach allows us to explore a range of OVS values and identify the configurations that achieve the desired SP while minimizing the LCOE.

The iterative process of the algorithm ends when all combinations of OVS and NDY have been analyzed. The results that meet the algorithm's constraints are saved in a table, where the minimum LCOE value is sought.

To introduce flexibility into the calculations, a range of variation for the SP target value is incorporated, allowing for a deviation of $\pm$0.5 from the desired value. This range accounts for uncertainties and fluctuations in electricity demand and generation, ensuring the system can still meet the specified objectives even under slightly altered conditions. In our study we explore the SP values within 50 % and 98 % with step of 10 %.

To account for the inherent variability in SP values, we excluded the possibility of achieving 100 % SP in the Lazio region due to the presence of existing renewable energy sources such as wind and hydro. These renewable sources already contribute to the region's energy production and cover approximately up to 10 % of the overall electricity demand.

3.3. Data

The study presented in this paper aims to assess the feasibility of achieving a high penetration of renewable energy in the Lazio region of Italy. To conduct this analysis, the latest available data for the three-year period from 2017 to 2019 were utilized. The decision was made to exclude data from 2020 and 2021 due to potential distortions caused by the impact of the COVID-19 pandemic.

Several key datasets were collected on an hourly basis to support the analysis:

- Regional electricity demand.
- Solar irradiance.
- PV production.
- Production from wind energy.
- Cost learning curves.

3.3.1. Regional electricity demand

The load profile of the Lazio region was derived by extrapolating from the data provided by the Italian TSO, Terna (TERNA, 2023a). Terna's data is aggregated on a quarter-hourly basis for the Central-South market area, which encompasses Lazio, Campania, and Abruzzo. By utilizing the annual statistical reports of each region (TERNA, 2023b) the percentage of Lazio's total annual electric demand was determined over the Central-South market area. This percentage was then applied to scale the regional electricity demand from the aggregated data, enabling the estimation of Lazio's specific load profile. It should be noted that while the obtained data may not perfectly reflect the actual values and profile, it provides a reasonable approximation. It is worth noting that Fig. 2 showcases an illustrative example of the electrical load for the year 2019, focusing on the daily, weekly, and monthly variations specifically for the month of July. This example serves to visually demonstrate the characteristics of the electrical load in the region during a specific period.

3.3.2. Solar irradiance

The solar resource available was estimated using satellite-derived irradiance provided by IDEAM (IDEAM, 2023) on 76 points according to a grid of 12x12km^2 covering the Lazio region (Fig. 3). The solar hourly data spatially averaged over the entire region was then used as input of a physical based model to calculate the regional PV generation as it was produced by a virtual power plant.

3.3.3. PV production

To calculate the hourly electricity production from photovoltaics, the SAPM (Sandia Array Performance Model) model was used (SANDIA, 2023), which was applied to each the 76 solar radiation time series of Fig. 3 and then spatially averaged over a virtual plant that is representative of the global production of the region.

Using this model, a sensitivity analysis was performed on the influence of the orientation and tilt of the panels on the photovoltaic production. Different tilt angles were evaluated for each orientation from east to west passing through the south (every 30°). The tilt angles considered range from 0 to 30° in steps of 5°.

For each simulation, the total energy obtained was compared with the annual photovoltaic energy provided by the TSO (Terna) to determine the "Plane of the Array" that best approximates the actual PV production in the Lazio region.

Fig. 4 shows the hourly trend of the Global Tilted Irradiance (GTI) and the ratio between the power produced and the nominal power (P/Pn) for a virtual power plant south oriented 10° tilted which best represents the real photovoltaic production of the Lazio region in 2019. This configuration was then used to simulate PV production for the three-year testing period.

3.3.4. Wind production

Given that in the Lazio region the production of electricity from wind is about 1 % (see section "PER LAZIO 2022"), therefore it is not sufficient to contribute significantly to create a high penetration scenario of VRE (PV and wind).

It was therefore decided to consider the possibility of importing electricity produced by wind from the southern area of the market which has a high wind production, the total installed capacity is for 2019 equal to 5.4 GW for a total energy production of 10.72 TWh. Hourly wind production data were obtained from Terna.

The market purchase price of the wind resource has been set at an

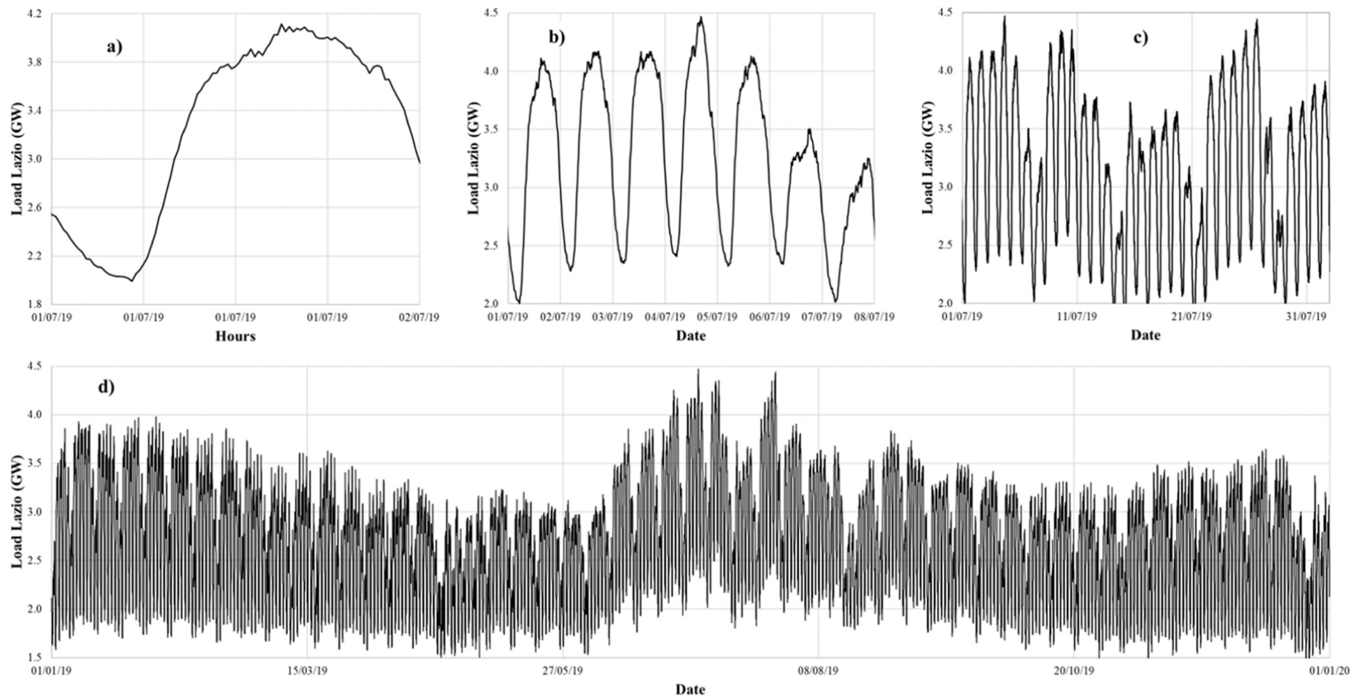

Fig. 2. Lazio Region load in 2019, a) daily, b) weekly, c) monthly and d) yearly trends.

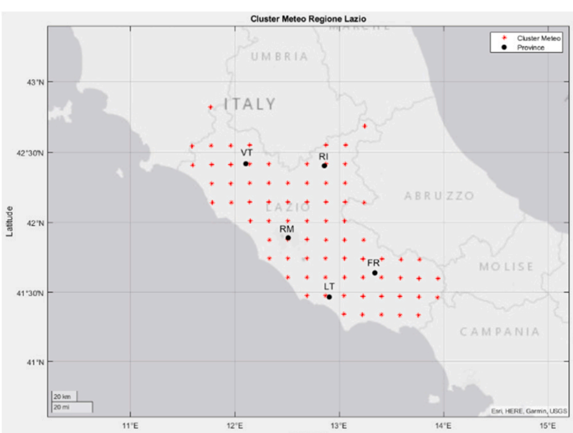

Fig. 3. 76 cluster for Lazio region (VT = Viterbo, RI = Rieti, RM = Rome, LT = Latina).

average value of 50 €/MWh for the entire year. As for production data, it consists of a time series from the southern market zone corresponding to the same year considered in the simulations (2019).

3.3.5. *Cost learning curve*

The scenarios studied in this paper are based on different costs for PV and BESS, and the values considered refer to the years 2023, 2030, 2040 and 2050. The simulations utilized the Capital Expenditure (CAPEX) values for PV and BESS (commercial/utility scale) provided by NREL (National Renewable Energy Laboratory) (NREL, 2023a; Steckel et al., 2021). For the lithium battery storage system an energy power ratio of 4 hour has been assumed.

NREL presents three different scenarios, conservative, moderate and advanced. As regards 2023, the conservative values were used, while for the future projections those of the moderate hypothesis.

We also assumed the following other costs for the storage:

- fixed O&M cost of 7.2 $/kW per year and a variable cost 3.1 €/MWh (ARERA, 2023).
- End of life (EoL) and dept-of-discharge (DOD) of 80 %
- round trip efficiency of 90 %.
- time degradation of 1.3 %,
- cycle degradation of 0.0045 % per fully cycle
- 5000 life cycle.

And for the PV:

- OPEX (Operational Expenditure) equal to 2 % of CAPEX per year;
- WACC (Weighted Average Cost of Capital) of 7 % per year;
- Inflation 2 % per year;
- PRL (Power Ramp Limitation) of 0.5 % per year

Fig. 5 shows the CAPEX trends for PV and BESS under the three different scenarios were used.

4. Results

In this paper, two cases were simulated. In the first one (PV+BESS), the electricity demand of the Lazio region is covered by photovoltaics and batteries. For this case, different CAPEX costs were assumed for both, using data provided by NREL, as described in the previous paragraph. Different values of VRE self-production in electricity demand were simulated, from 50 % to 100 % in 10 % increments. The results also provided a trend of LCOE versus VRE penetration.

The second case (PV+BESS+WIND imp), considers the possibility of import the 25, 50, 75 and 100 % of wind production of the southern market area of. In these simulations, the CAPEX of PV and BESS were set to the values estimated for 2050 and the import of wind energy cost is set at the National Unique Price (PUN). This second scenario was adopted to limit the capacities of PV and BESS. Importation is considered instead of wind installation because, unlike solar, wind sites are very limited in the Lazio Region (however, an increase in wind capacity can be achieved by repowering existing plants).

Similar to the first scenario (PV+BESS), VRE self-production was investigated from 50 % to 100 % in 10 % increments.

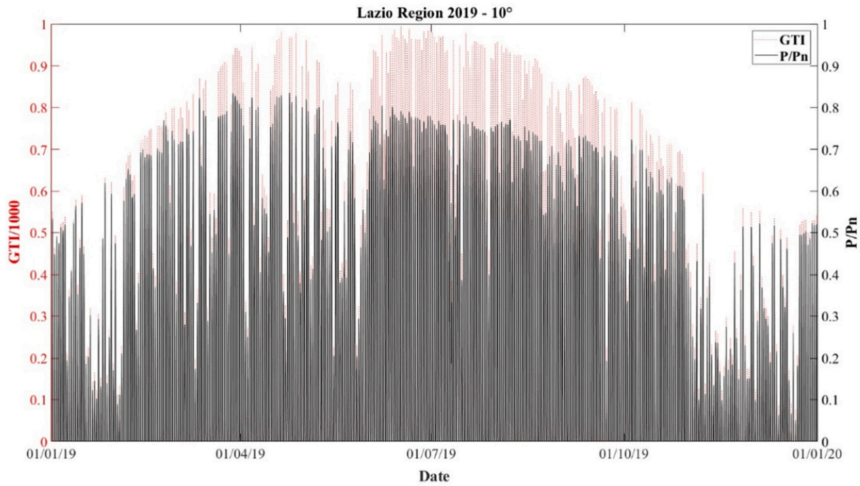

Fig. 4. PV production and GTI for Lazio region in 2019.

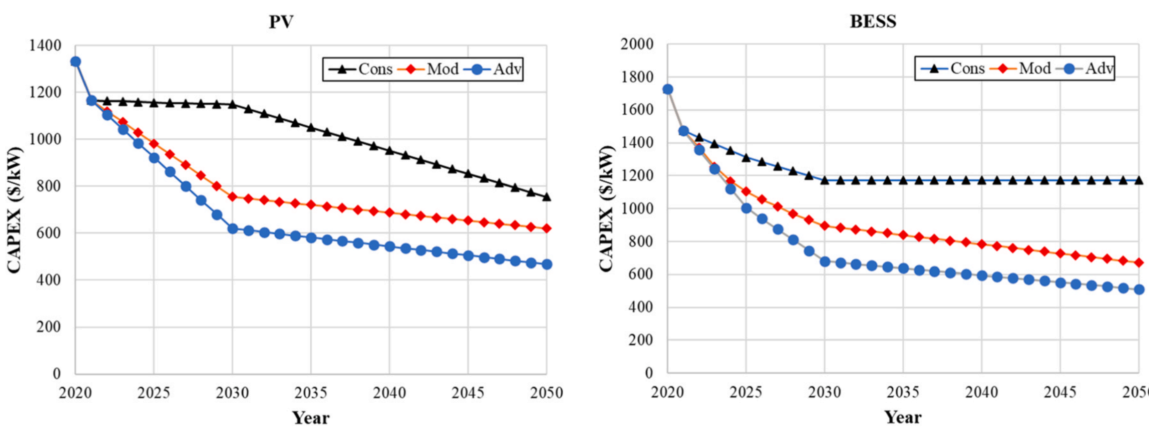

Fig. 5. - PV and BESS CAPEX trends by NREL (NREL, 2023a, 2023b.

For both cases, the LCOE was calculated together with the numbers of daily electric demand to be stored and the BESS hours.

The LCOE for both scenarios are calculated as a weighted average of the single components involved in the total energy demand: the energy fed into the grid by the batteries multiplied by the LCOS of the batteries, the residual electricity demand (if any) and the wind import energy (if any) multiplied by the purchase cost (PUN), the PV production used to meet the load or recharge the storage multiplied by the LCOE of PV computed considering the required proactive curtailment.

Even if in this work we'll present and discuss the results for SP=90 % we extended the simulation up to 98 % to investigate the possibility of limiting the use of hydro due to the droughts of recent years.

4.1. Scenario 1: PV+BESS

As mentioned in the methodology section, the simulations were conducted for varying Solar Penetration (SP) levels ranging from 50 % to 100 %. For the purpose of this discussion, the results pertaining to SP = 90 % will be presented in detail. This value was selected to consider the coexistence of other renewable resources that are already established within the area. By opting for SP = 90 %, the analysis considers the optimal balance between the integration of flexible photovoltaic generation and the existing renewable energy sources, ensuring a comprehensive evaluation of the region's energy landscape.

Fig. 6 shows the simulation result for SP = 90 %. The graph shows the trends of NDY as a function of OVS (Fig. 6a), BESS hours as a function of PV curtailment (Fig. 6b) and LCOE as a function of OVS (Fig. 6c). As described earlier (section "Optimization process"), the optimization process searches through all possible configurations in search of the minimum LCOE (Fig. 6c), with the corresponding values of OVS and NDY, satisfying SP settled.

In particular, Fig. 6c shows how an increase in OVS leads to a progressive reduction in LCOE until an optimal value is reached, beyond which further increases in OVS lead to an increase in cost. Although the BESS cost is reducing the LCOE increases is mainly due to two factors: firstly, the cost of PV oversizing and secondly, the cost of curtailment (which obviously increases with the oversizing, Fig. 6b).

Fig. 6a shows a decrease in NDY, which, as mentioned above, is accompanied by an increase in fully equivalent cycles per year. Without oversizing the PV, continuous generation will require seasonal storage (about 90 days in our case), so this solution is completely economically unfeasible and technically ineffective. Fig. 7 shows that this huge amount of storage is hardly used, realizing only 6 fully equivalent cycles per 3 years.

With PV oversize, this capacity could be reduced to a minimum value:1 day or less. The cost-effective OVS value is determined by the minimum LCOE (Fig. 6c). This reduction in battery capacity leads to an obvious increase in fully equivalent cycles per year, that makes the batteries to be effectively used, however it must be considered in the LCOS. As shown in Fig. 7 the number of full equivalent cycles per 3 years increases from 6 for seasonal storage to a value of 782 for the optimum configuration (~261 cycles per year).

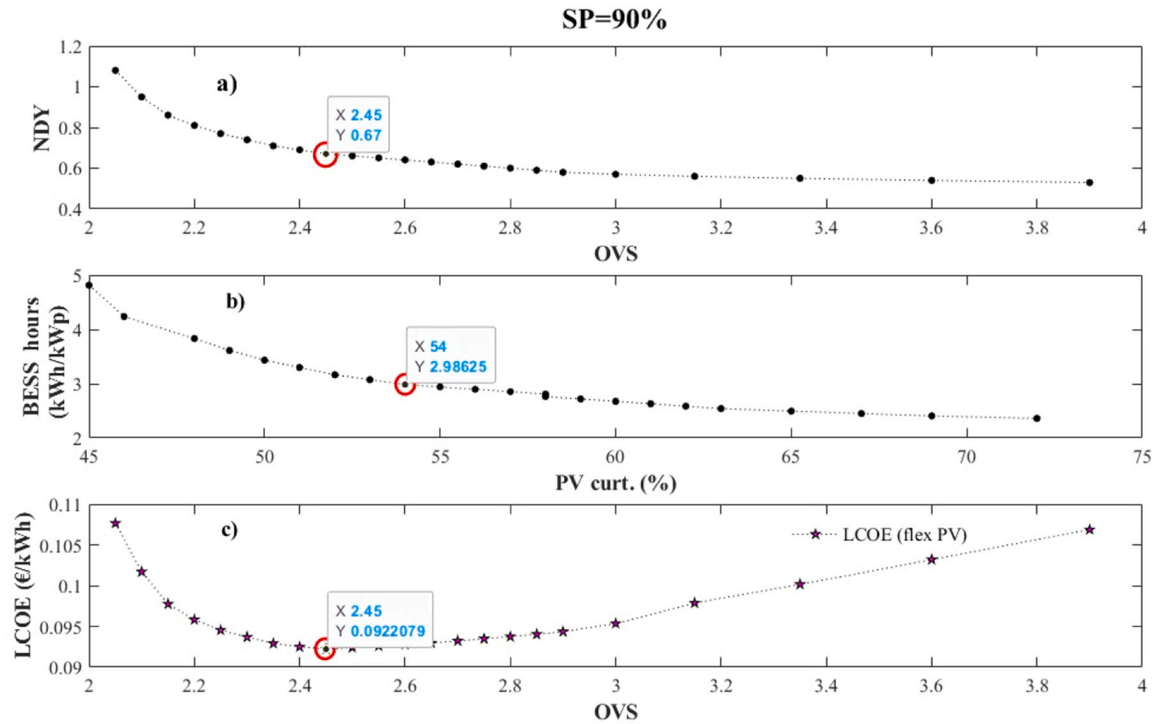

Fig. 6. Simulation results for SP = 90 % showing trends of NDY, LCOE as a function of oversize and BESS hours as function of PV curtailment.

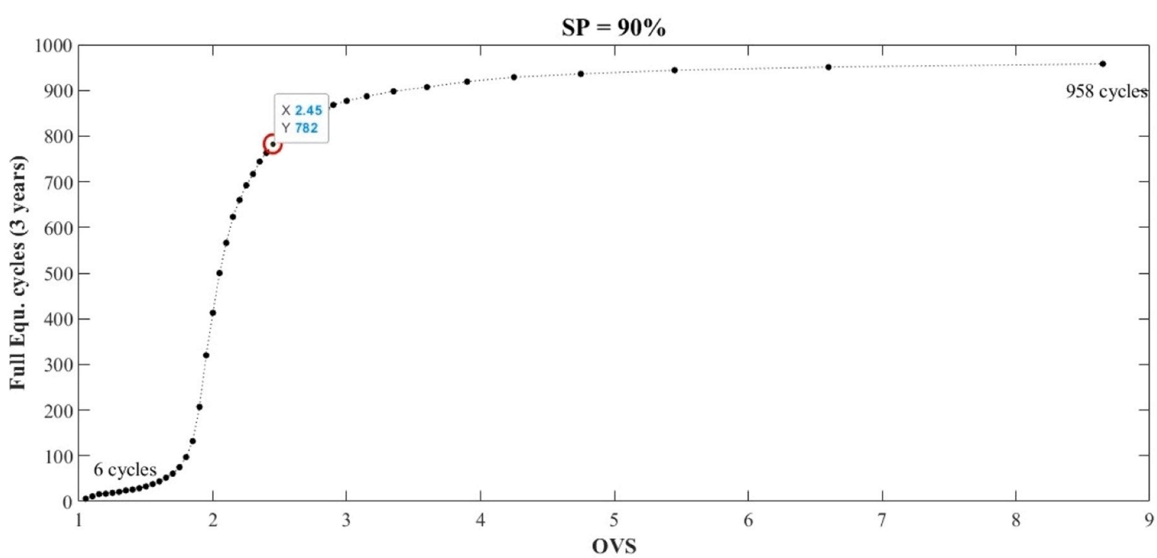

Fig. 7. Full equivalent cycles for the PV case as a function of oversize for SP = 90 % over three years.

Fig. 8 summarizes the results of all simulations carried out for the first case (PV+BESS).

In particular, Fig. 8a shows that the trend of PV capacity is almost linear up to 80 % of electricity demand and then undergoes an increase of 50 % (compared to the previous value) at SP = 90 % and a doubling (compared to 90 %) at a SP = 98 %.

This increase in capacity is mainly due to the need to eliminate the residual load present in the winter season at 80 and 90 % self-production (Fig. 9a and Fig. 9b). Residual load is almost eliminate at SP=98 % (Fig. 9c) by oversizing PV and optimizing the battery, this leads to a daily average State of Charge (SOC) of the battery about 50 % and consequently an increase of daily equivalent cycles.

As a result, the oversize was found to increase from a value of 1.65 at SP = 80 % to 2.45 at SP = 90 % and 5 at SP = 100 %. This result can also be seen in Fig. 8b, which shows the trend of curtailment as a function of SP.

As for the BESS capacity, it can be seen from Fig. 8a that the growth trend is linear until SP = 90 %, after which the capacity increases by 75 %.

Fig. 8c shows the trend of the minimum value of LCOE function of the self-production. The LCOE (Fig. 8c) is therefore influenced by this trends and shows acceptable values up to SP = 90 % even at current costs, the LCOE value ranges from a minimum of 0.092 €/kWh (2050) to a maximum of 0.172 €/kWh (2023). The corresponding PV and BESS

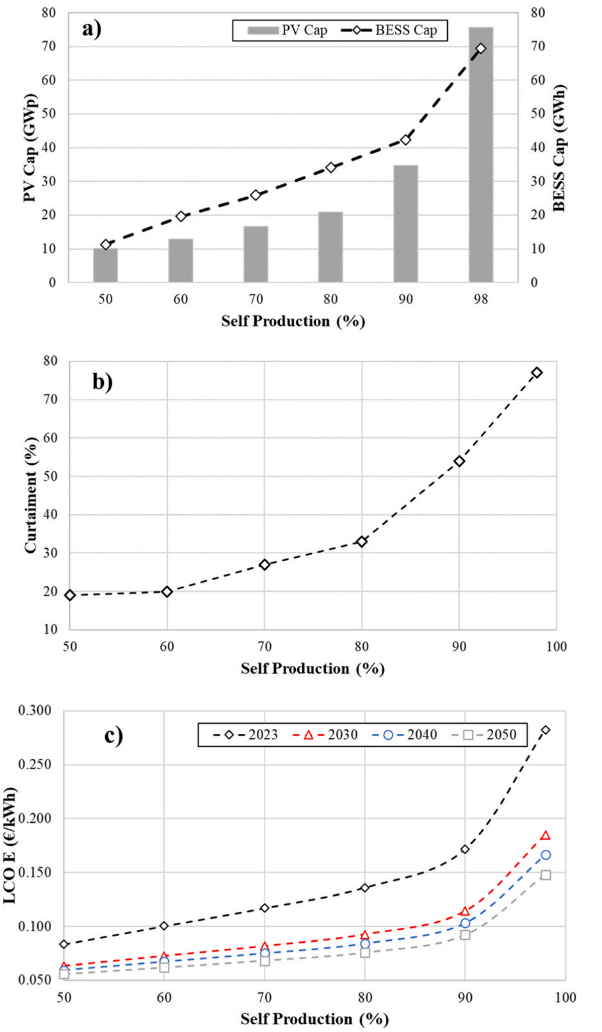

Fig. 8. Simulation results for the PV case as a function of self-production, a) PV and BESS capacity, b) Curtailment and c) minimum LCOE.

capacity are respectively 34.73 GWp and 42.34 GWh.

For SP = 98 %, the only feasible scenarios are those related to the costs foreseen for 2040 (0.167 €/kWh) and 2050 (0.148 €/kWh).

The simulations went up to a self-production value of 98 % to investigate the possibility of limiting the use of hydro due to the droughts of recent years as stated before.

Based on the results of the simulations for this scenario, it was decided to evaluate the import of wind, the results of which are described in the following subsection.

4.2. *Scenario 2: PV+BESS+Wind import*

In the second simulated scenario a deliberate decision was made to incorporate the importation of electricity derived from wind power generated in the southern market area, encompassing Puglia, Calabria, Molise, and Basilicata. To comprehensively explore the potential impact of this choice, four distinct cases were considered, each representing a different proportion of electricity production sourced from wind power. Specifically, the scenarios included 25 %, 50 %, 75 %, and 100 % of the total electricity generation derived from wind power sources.

To establish a robust foundation for the analysis, the costs associated with PV systems and battery energy storage were aligned with those projected for the year 2050. By employing these future cost estimates, the simulations accounted for the anticipated advancements in technology and economies of scale that are expected to drive down the costs of PV systems and batteries over time.

Furthermore, it was assumed that the imported wind energy would be priced equivalently to the PUN index, which represents the average national electricity price in Italy. This assumption ensures consistency in the economic evaluation by aligning the cost of the imported wind energy with the prevailing market conditions.

By considering these factors, the simulation scenario explores the potential synergistic effects of importing wind energy alongside the deployment of photovoltaic systems and energy storage, thus offering valuable insights into the feasibility and economic viability of a combined renewable energy approach.

Similar to the previous case, Fig. 10 and Fig. 11 show the results of the simulations for SP = 90 % and wind imports of 25 % of wind production (Fig. 10) and 50 % (Fig. 11).

It can be seen that the LCOE minimum (Figs. 10c and 11c) is found at lower OVS values than in the previous case, but at a higher cost, even though the PV and BESS capacity are lower, since the cost of buying wind energy at the market price has a much greater impact on the LCOE than the reduction in PV and BESS capacity.

It can also be seen (Figs. 10a and 11a) that there is a reduction in NDY. This is mainly due to the different variability of wind resource (also available at night) compared to PV (only available during the day). The NDY reduction results in an increase in number of full equivalent cycles with respect to the PV+BESS case for 25 % wind import (805 cycles) and a reduction for 50 % wind import (~250 cycles per year).

Comparing the NDY of Fig. 10a with that of Fig. 11a, we can see that despite the decrease in NDY, the number of cycles does not increase as one would expect, which can be justified by the greater stability of the wind resources.

Fig. 12, Fig. 13 and Table 2 summarize the results of all the simulations carried out for this case (PV+BESS+Wind Import).

Fig. 12 shows that wind import could not be applied to all scenarios, in particular minimizing LCOE did not yield values for SP lower than 80 % in the case of 100 % wind import. The same is true for 75 % for SP lower than 70 %.

Comparing the results of Fig. 12 with those of Fig. 8c, we can notice that, as expected, the introduction of wind import causes an overall increase in costs due to the cost of purchasing the resource.

If we focus on the 25 % and 50 % imports and compare the LCOE in Fig. 12 with the 2040 and 2050 scenario of Fig. 8c (grey and blue curves) the result is reported in Fig. 13. The graph in Fig. 13 shows that a wind import of 25 and 50 % for a SP of 90 % results in costs comparable to the 2040 scenario: 0.098 €/kWh (25 % wind import), 0.106 €/kWh (50 % wind import) and 0.103 €/kWh (2040 scenario), respectively. If we compare them instead with the 2050 scenario (0.092 €/kWh), they are significantly higher but still reasonable, so the two wind import value can be used.

Table 2 summarizes the PV and BESS capacity and reduction achievable by importing wind energy.

With the focus on the high values of SP (> 80 %), we can see from Table 2 that with the same SP the increase in wind imports shows an increase in the reduction of both photovoltaic capacity and batteries, but at the expense of a growing LCOE (see Fig. 8c and Fig. 12).

For SP = 90 %, 25 % wind import reduces the capacity of the photovoltaic system by 6.4 % and that of the batteries by 9.1 %. Increasing the percentage of wind imports (50 %), the capacity reduction is 13.2 and 14.8 % respectively.

5. Discussion

This study provides valuable insights into the feasibility of implementing flexible photovoltaic generation in the Lazio region, offering a model that can be replicated in similar regions. The aim was to evaluate the potential for achieving the region's ambitious goal of generating 100 % of its electricity from renewable sources by 2050. Through

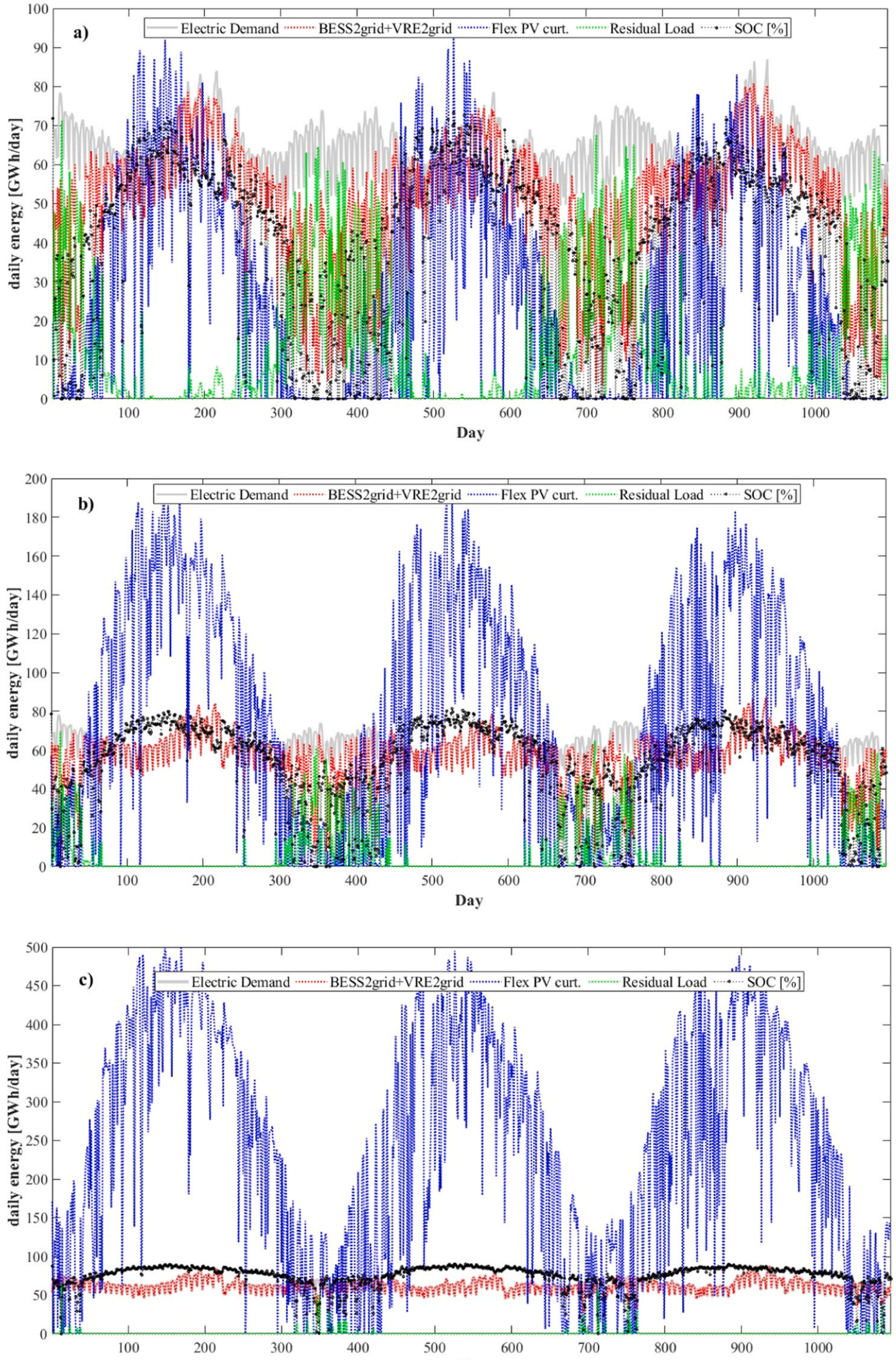

Fig. 9. Daily energy balance for PV case over three year: a) SP = 80 %, b) SP = 90 % and c) SP = 98 %.

comprehensive simulations and analyses, various scenarios were examined, considering the projected costs of photovoltaic systems and battery energy storage systems until 2050, as well as the impact of wind energy imports on the required PV and BESS capacities.

Furthermore, the results of scenario 1 simulations were used to build a road map for the Lazio region to achieve 90 % renewable energy by 2050. The road map is divided into three steps (see Fig. 14), with each step representing a milestone for self-production to be achieved.

The self-production targets reported in the road map are 50 %, 70 %, and 90 % corresponding to 2030, 2040, and 2050, respectively. The road map also includes the PV and BESS capacity to be installed and the relative cost of LCOE.

The results provided by this study on flexible photovoltaic generation applied to the Lazio region lay the foundation for further in-depth discussions on key aspects related to renewable energy integration.

Building upon the findings, the following discussion points provide avenues for deeper exploration and critical analysis of the implications:

1. Role of Batteries and Cost Implications: The findings of this study emphasize the crucial role of battery energy storage systems in

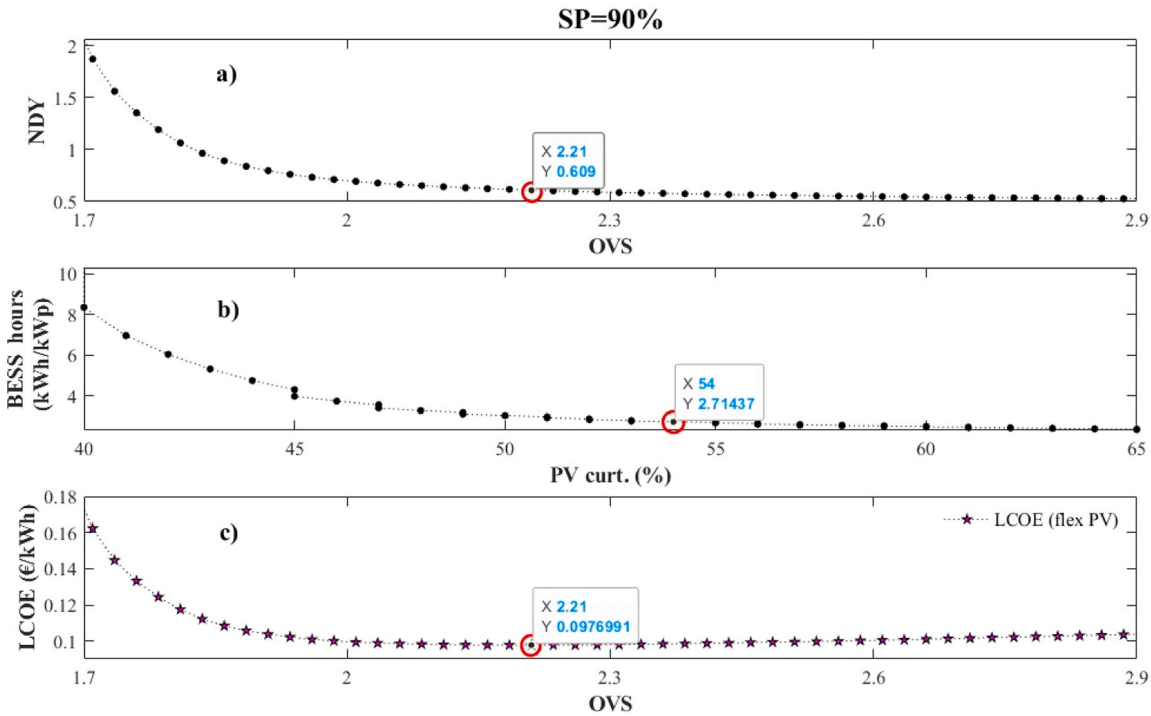

Fig. 10. Simulation results for SP = 90 % showing trends of NDY, LCOE as a function of oversize and BESS hours as function of PV curtailment with 25 % wind import.

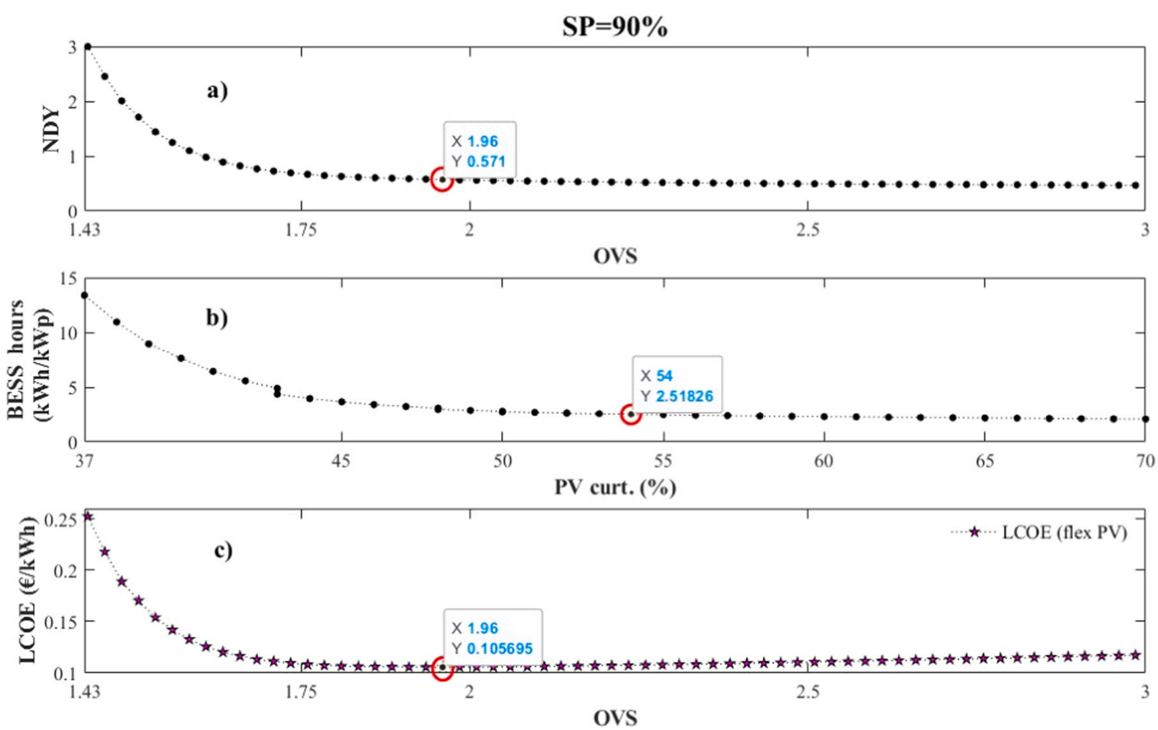

Fig. 11. Simulation results for SP = 90 % showing trends of NDY, LCOE as a function of oversize and BESS hours as function of PV curtailment with 50 % wind import.

supporting flexible photovoltaic generation. However, it is important to acknowledge that the high costs associated with BESS installations pose a significant challenge. Future research and development efforts should focus on improving battery technologies and reducing their costs to enhance the economic viability of renewable energy systems. Additionally, exploring alternative energy storage options such as pumped hydro storage or innovative battery chemistries could offer additional avenues for cost reduction and system optimization.

2. Agrivoltaics and Land Utilization: The study highlights the potential of agrivoltaics, a practice that combines solar energy generation with agricultural activities, to optimize land use efficiency. Given the substantial land area required for large-scale photovoltaic

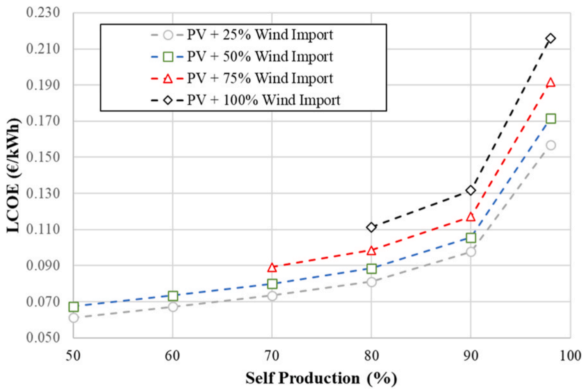

Fig. 12. LCOE of PV (2050 Scenario) + Wind Import at different import level as function of self-production.

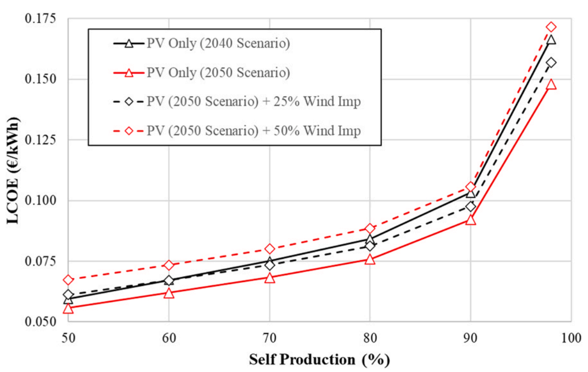

Fig. 13. LCOE comparison: only PV (2040 and 2050 cost scenario) and PV+wind import (25 and 50 %) as function of self-production.

installations, integrating PV systems into agricultural landscapes presents a dual benefit by enabling renewable energy production while preserving valuable land for food production. However, further research is needed to assess the agronomic impacts, economic viability, and social acceptance of agrivoltaics, considering factors such as crop yields, water usage, and land management practices.

3. Network Adaptations and Grid Integration: The successful integration of flexible photovoltaic generation at a large scale necessitates adaptations in the existing electricity network. The intermittent nature of renewable energy sources requires grid infrastructure upgrades, including smart grid technologies, advanced monitoring systems, and energy management solutions. Additionally, the deployment of energy storage systems, both centralized and distributed, can help enhance grid stability, balance supply and demand, and facilitate the integration of variable renewable energy sources. Collaborative efforts between policymakers, energy companies, and research institutions are essential to drive the necessary network upgrades for a seamless transition to high-penetration renewable energy systems.
4. Expansion to Other Regions and Comparative Studies: While this study focuses on the Lazio region as a case study, the methodologies and insights can be expanded to other regions in Italy and beyond. Conducting similar analyses in different geographical contexts allows for a comparative assessment of renewable energy potentials, policy frameworks, and infrastructure requirements. This broader perspective enables policymakers and energy planners to identify region-specific opportunities, challenges, and best practices, fostering a holistic approach to renewable energy deployment.
5. Multi-Stakeholder Collaboration: The successful implementation of flexible photovoltaic generation and the transition to a high-renewable energy system require collaboration among various stakeholders. Engaging local communities, energy companies, policymakers, research institutions, and non-governmental organizations is crucial to ensure a participatory approach that considers diverse perspectives, promotes social acceptance, and addresses any socio-economic concerns. Public awareness campaigns, capacity-building initiatives, and inclusive decision-making processes should be employed to create a shared vision and mobilize support for renewable energy development.

6. Conclusion

The conclusions drawn from this study are presented below in a detailed list, which highlights the key findings and their implications for the integration of renewable energy in the Lazio region:

- The Firm PV concept demonstrates that installing 34.73 GWp of PV capacity and 42.34 GWh of BESS can achieve 90 % renewable energy self-production for Lazio by 2050.
- Estimated Costs: The projected costs for achieving high levels of self-generation indicate an estimated dispatch cost of 92.21 €/MWh by 2050. These costs do not consider the potential revenue from selling

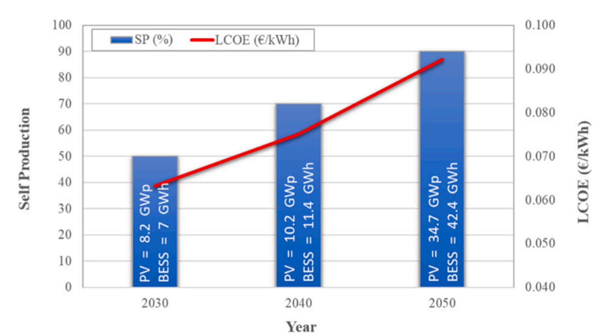

Fig. 14. Lazio region road map with PV and BESS capacity to be installed in 2030, 2040 and 2050.

Table 2
Comparison of PV and BESS capacities and reductions at various wind import percentages versus using only PV for different self-production levels.

SP	PV+BESS		PV+BESS+Wind Imp = 25 %				PV+BESS+Wind Imp = 50 %			
	PV (GWp)	BESS (GWh)	PV (GWp)	BESS (GWh)	ΔPV (%)	ΔBESS (%)	PV (GWp)	BESS (GWh)	ΔPV (%)	ΔBESS (%)
80	20.8	34.1	20.1	31.0	−3.4	−9.1	19.4	28.4	−6.8	−16.7
90	34.7	42.3	32.5	38.5	−6.4	−9.1	30.1	36.1	−13.2	−14.8
98	75.6	69.5	70.7	65.1	−6.6	−6.4	68.7	60.7	−9.1	−12.7
SP	PV+BESS		PV+BESS+Wind Imp = 75 %				PV+BESS+Wind Imp = 100 %			
	PV (GWp)	BESS (GWh)	PV (GWp)	BESS (GWh)	ΔPV (%)	ΔBESS (%)	PV (GWp)	BESS (GWh)	ΔPV (%)	ΔBESS (%)
80	20.8	34.1	19.3	25.9	−7.3	−24.1	19.3	24.5	−7.0	−28.1
90	34.7	42.3	28.8	34.0	−17.0	−19.7	27.4	33.5	−21.1	−20.9
98	75.6	69.5	65.3	60.0	−13.7	−13.6	63.4	59.1	−16.2	−15.0

surplus photovoltaic production, which is dynamically curtailed in the simulations. While the costs are relatively high, they are still half of today's price cap set by the EU for energy produced from renewable sources thus they can be considered acceptable given the ambitious renewable energy targets.
- Utilization of Potential Area: The estimated potential of Agri-PV in the Lazio region is 266 GWp, covering an area of 8000 km^2. The study reveals that using only 13 % of this potential area would be sufficient to meet the required capacity, highlighting the region's ample potential for photovoltaic installations.
- Wind Import Impact: Simulations incorporating the importation of wind energy from neighboring regions demonstrate the feasibility of reducing the PV capacity by utilizing other renewable resources. However, it was observed that such imports increased costs by 6.5 % (25 % wind import) and 13.5 % (50 % wind import) compared to the 2050 scenario without wind imports. Additionally, the installed capacity of both PV and BESS decreased by 6.4 % and 9.1 % (25 % wind import) and by 13.2 % and 14.8 % (50 % wind import). Hence, as far as possible, increasing the installed wind capacity within the Lazio region is desirable.
- Wind Energy Production Projections: According to the PER2022 projections, the wind capacity in the Lazio region is not expected to exceed 1.2 GW (offshore + onshore) by 2050, with an estimated production of 3800 GWh. This wind energy production represents an intermediate value between the simulated wind import scenarios (25 % and 50 %) and could be a valuable consideration for future scenarios, contributing approximately 35 % of the imported energy from the South.
- Cost Advantage of Lazio Wind Resource: Considering that the Levelized Cost of Energy (LCOE) for wind resources in the Lazio region is lower than the purchase cost (PUN), it is anticipated that the overall LCOE of the system would be reduced. Consequently, the integration of wind energy alongside PV generation could facilitate the development of a cost-effective VRE mix, potentially surpassing the cost of importing energy.
- Moreover, it was demonstrated that the findings from scenario 1 (PV + BESS) can be used to develop a road map to increase renewable energy penetration in the Lazio region. The findings of this study will serve as the basis for a prototype PV+BESS power plant, where the concept of firm PV generation will be applied and verified.

In conclusion, the discussions presented here shed light on several important aspects related to the role of batteries, agrivoltaics, network adaptations, expansion to other regions, and stakeholder collaboration. Addressing these considerations will facilitate the transition towards a sustainable and resilient energy future, maximizing the potential of flexible photovoltaic generation and advancing renewable energy goals at regional and national scales.

CRediT authorship contribution statement

Marcello Petitta: Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Cristina Cornaro:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Software, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Gianluigi Bovesecchi:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marco Pierro:** Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Gianluigi Bovesecchi reports financial support was provided by Lazio Region. Gianluigi Bovesecchi reports financial support was provided by Graphene Flagship. Marcello Petitta reports financial support was provided by European Union. Cristina Cornaro reports financial support was provided by Horizon Europe. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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