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SCUOLA DI INGEGNERIA INDUSTRIALE
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EXECUTIVE SUMMARY OF THE THESIS

Estimation of Frequency Reserve Requirement & Evaluation of BESS Dispatch Strategy for the 2030 Italian Electricity Market

TESI MAGISTRALE IN ENERGY ENGINEERING – INGEGNERIA ENERGETICA

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1. Introduction

The increasing integration of renewable energy sources into power systems has introduced new challenges in balancing supply and demand, primarily due to the variability of wind and solar generation [1]. Italy, under its National Energy and Climate Plan (NECP) 2030, aims to significantly expand its renewable energy capacity, necessitating a robust approach to reserve estimation to ensure system reliability [2]. The shift towards a high-renewable power system demands reserve planning to maintain stability and prevent grid imbalances caused by fluctuations. Accurate reserve estimation is crucial to maintaining system security while optimizing economic efficiency [3]. This research focuses on reserve estimation methodologies to address uncertainties in Italy's 2030 power system and evaluation the BESS dispatch strategy to accommodate the RES time-shifting and reserves requirement. To achieve this, the study employs two distinct reserve estimation methodologies: the formula-based approach and the convolution method [4]. The formula-based approach applies to deterministic calculations using forecast errors and standard deviations to determine reserve sizing, often resulting in conservative estimates to ensure grid reliability. The convolution method, on the other hand, applies a probabilistic framework, integrating individual probability distributions of forecast errors to provide a refined estimation that incorporates statistical correlation effects. To complement the reserve estimation analysis, this study investigates the operational and economic role of BESS in 2030. Using electricity price signals to guide a realistic dispatch strategy, the analysis evaluates how a national-scale BESS fleet can first perform time shifting and subsequently provide upward and downward frequency reserves

2. Methodologies

The overall methodology of the study is represented in Figure 1.

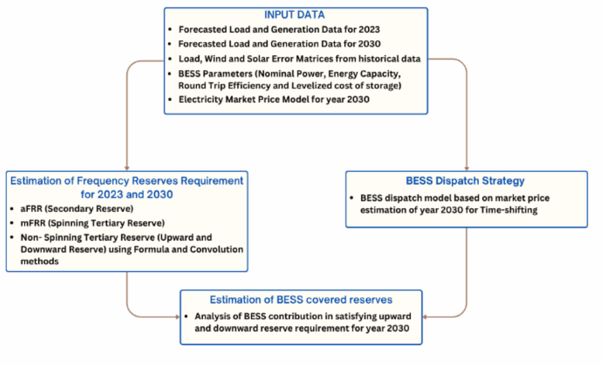

Figure 1. Overall Methodological approach

2.1 Data Acquisition and Processing

The 2023 dataset was obtained from Terna, Italy's Transmission System Operator (TSO), consisting of hourly load data and renewable generation data (wind and solar) [5]. To project the 2030 electricity demand profile, a bottom-up modeling approach was applied to 2023 baseline data, incorporating sector-specific electrification trends such as heat pumps, EVs, and industrial electrification. The final demand was scaled by 88.3% to reflect EU efficiency targets [6], [7]. For renewable generation, Italy's NECP 2030 targets project wind capacity to increase by 2.28x and solar by 2.61x [2].

2.2 Formulation of Error Matrices

To estimate reserve requirements under forecast uncertainty, this study employs empirical error matrices for load, solar, and wind generation, derived from historical data in Bovera et al [3]. These matrices link forecasted values to their expected errors and are applied hourly to compute standard deviations of forecast errors in megawatts, which represents the expected variability and forms the basis for reserve estimation in both methods.

2.3 Calculation of Spinning and Non-Spinning Reserves

The automatic frequency restoration reserve (aFRR) and manual frequency restoration reserve (mFRR) were estimated using Eq.1 and Eq.2:

- aFRR Calculation [3]:

$$aFRR_{k,i} = \sqrt{a * L_{max,k,i} + b^2} - b \tag{1}$$

- mFRR Calculation:

$$mFRR_{k,i} = aFRR_{k,i} * (1 + \left|LoadRamp_{k,i}\right|) \tag{2a}$$

$$LoadRamp_{k,i} = \left|\frac{L_i - L_{i-1}}{L_i}\right| \tag{2b}$$

Non-spinning reserves provide additional flexibility by addressing imbalances that exceed the capabilities of spinning reserves. The reserve requirement is determined using Eq.3.

$$RR_{N\,spin} = Pmax + 2.74 * \sigma_{Total} \tag{3}$$

where Pmax represents the maximum capacity of key generation assets, including thermoelectric plants for upward reserves (2000 MW in 2023, 881 MW in 2030) [8][9] and pumped hydro plants for downward reserves (1065 MW in 2023, 1184 MW in 2030) [10][11]. To quantify σ_{total}, two estimation methods were applied, Formula Based Method and Convolution Method. The formula-based method analytically estimates the total standard deviation of forecast errors. The total standard deviation is computed in Eq.4.

$$\sigma_{total} = \sqrt{\sigma_{load}^2 + \sigma_{solar}^2 + \sigma_{wind}^2 + 2\rho.\sigma_{load}.\sqrt{\sigma_{solar}^2 + \sigma_{wind}^2}} \tag{4}$$

where ϱ, the correlation coefficient between load and renewable forecast errors, is 0.05 for 2023 and 0.025 for 2030, reflecting reduced correlation in 2030 due to increased renewable penetration. The convolution method is a probabilistic approach used to estimate total forecast uncertainty by integrating the probability distribution of forecast errors in load, wind, and solar generation. represented by Eq.5.

$$\sigma_{REN}^2 = \sigma_{SOLAR}^2 + \sigma_{WIND}^2 \tag{5}$$

Next, the total renewable uncertainty is combined with load forecast errors through another convolution, represented by Eq.6.

$$\sigma_{TOTAL}^2 = \sigma_{LOAD}^2 + \sigma_{REN}^2 \tag{6}$$

The total standard deviation (σ_{TOTAL}) obtained from this final probability distribution serves as the basis for determining non-spinning reserve requirements

2.4 BESS Dispatch Strategy

To evaluate the contribution of BESS to reserve requirements in 2030, a dispatch model was implemented using hourly market marginal cost (MC) signals. The BESS is characterized by a nominal power of 8.33 GW, energy capacity of 50 GWh, round-trip efficiency of 96%, and a levelized cost of storage (LCOS) of €50/MWh [2]. The model applies a 12-hour rolling window to identify arbitrage opportunities. Operation is allowed only if the spread in market prices exceeds the LCOS. Within eligible windows, a profitability threshold is defined in Eq.7:

$$Threshold = MC_{avg} + \frac{LCOS}{2} \tag{7}$$

Discharge occurs when MC > Threshold, charge when MC < Threshold, and idle otherwise. The SoC dynamically evolves in Eq.8:

$$SoC_t = min\left(E_{max}, max\left(0, SoC_{t-1} - \frac{P_{ch,req}}{\eta_{rtrp}} + P_{dis,req} * \eta_{rtrp}\right)\right) \quad (8)$$

with power requests based on flag values and nominal power. Real charging/discharging values are calculated from SoC changes and then used to assess BESS contributions to hourly upward and downward reserves.

2.5 RES Time-shifting and reserve contribution

The study simulates a market-driven dispatch strategy where the BESS charges during low-price hours and discharges during high-price periods, enabling effective renewable energy time shifting. As shown in the Figure 2, battery SoC dynamically follows price patterns throughout the year, reflecting economically optimized cycling behavior. This strategy allows BESS to reduce curtailment of excess renewable generation and provide peak shaving when system demand is high. A total of 11 TWh was discharged annually, with the system performing approximately 214 equivalent full cycles. These operations form the foundation for subsequent reserve availability.

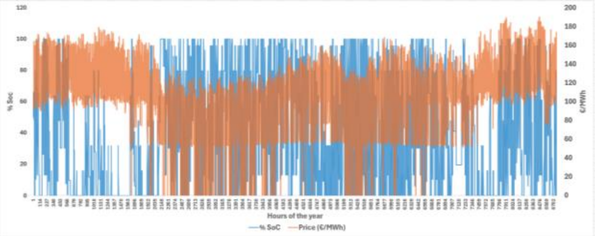

Figure 2. % SoC BESS and market prices - 2030

To assess the contribution of BESS to system reserves in 2030, the model simulates hourly operations of a national-scale BESS fleet (8.33 GW power, 50 GWh energy capacity) based on 2030 electricity market price signals and evaluates available reserve capacity considering SoC constraints. Three operating scenarios are modeled:

1) Idle State: (No active Charging or Discharging):

$$R_{up} = \begin{cases} P_{nom}, \ if\ E_{nom}.SoC \geq P_{nom} \\ E_{nom}.SoC, \ if\ E_{nom}.SoC \leq P_{nom} \end{cases} \quad (9)$$

$$R_{down} = \begin{cases} -P_{nom}, \ if\ E_{nom}.(1 - SoC) \geq P_{nom} \\ -E_{nom}.(1 - SoC), \ if\ E_{nom}.(1 - SoC) \leq P_{nom} \end{cases} \quad (10)$$

2) Discharging State (Pdis > 0)

$$R_{up} = \begin{cases} P_{nom} - P_{dis}, \ if\ E_{nom}.SoC \geq (P_{nom} - P_{dis}) \\ E_{nom}.SoC, \ if\ E_{nom}.SoC \leq (P_{nom} - P_{dis}) \end{cases} \quad (11)$$

$$R_{down} = \begin{cases} -(P_{nom} + P_{dis}), \ if\ E_{nom}.(1 - SoC) \geq P_{nom} \\ -E_{nom}.(1 - SoC) - P_{dis}, \ if\ E_{nom}.(1 - SoC) \leq P_{nom} \end{cases} \quad (12)$$

2) Charging State (Pch < 0)

$$R_{up} = \begin{cases} P_{nom} - P_{ch}, \ if\ E_{nom}.SoC \geq P_{nom} \\ E_{nom}.SoC - P_{ch}, \ if\ E_{nom}.SoC \leq P_{nom} \end{cases} \quad (13)$$

$$R_{down} = \begin{cases} -(P_{nom} + P_{ch}), \ if\ E_{nom}.(1 - SoC) \geq P_{nom} + P_{ch} \\ -E_{nom}.(1 - SoC) - P_{ch}, \ if\ E_{nom}.(1 - SoC) \leq P_{nom} + P_{ch} \end{cases} \quad (14)$$

3. Results

This section presents the reserve estimation results for Italy's power system in 2023 and 2030, highlighting the role of BESS system in time-shifting and reserve provision.

3.1 Reserve Estimation for 2023 and 2030

Figure 3 shows the secondary reserve (aFRR) requirements for the year 2023 and 2030. Comparison highlights a clear trend and a noticeable increase in variability and peak reserve need in 2030.

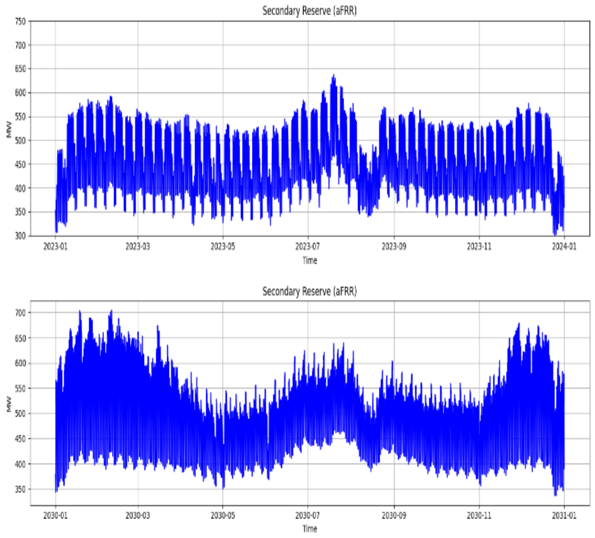

Figure 3. Secondary Reserve Requirement hourly profile 2023 (up) & 2030 (down)

Figure 4 represents the non-spinning upward requirement hourly profile for 2023 and 2030 using formula method. A clear increase in both magnitude and volatility is observed in 2030 with peaks exceeding 14000MW compared to more stable profile averaging 5000MW in 2023.

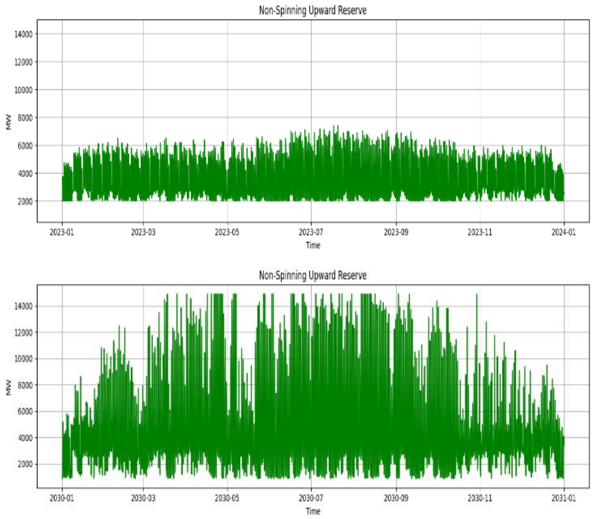

Figure 4. Upward Reserve Requirement Profile 2023 (up) and 2030 (down) using Formula Method

The non-spinning tertiary reserves indicate a significant rise in 2030, with upward reserves increasing from 3791 MW (2023) to 4868 MW (2030) and downward reserves from 2856 MW (2023) to 5171 MW (2030) using the formula-based method as shown in Table 1. The convolution method estimates higher reserve requirements, with downward reserves reaching 5585 MW in 2030, highlighting the difference between conservative (formula-based) and probabilistic (convolution) reserve estimation approaches.

Table 1. Parameters Breakdown 2023 and 2030

Parameters	2023 (MW) (Formula)	2023 (MW) (Conv.)	2030 (MW) (Formula)	2030 (MW) (Conv.)
Total Std.Dev (σ_{total})	654	805	1455	1606
Reserve Requirement (2.74 σ_{total})	1791	2205	3987	4401
RR Non-Spinning Upward	3791	4205	4868	5282
RR Non-Spinning Downward	2856	3270	5171	5585

The formula-based method was selected for further analysis as it provides more accurate reserve estimates, ensuring system reliability. It also aligns ENTSO-E guidelines, making it more applicable for real-world grid planning and regulatory compliance [3].

Figure 5 represents a comparison between upward and downward imbalances with upward and downward reserves on hourly basis for year 2023.

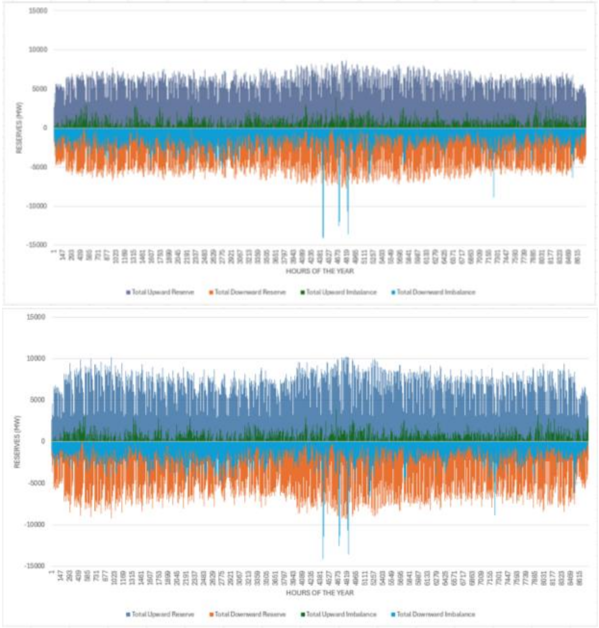

Figure 5. Comparison of Reserves and Imbalances Hourly Profile- 2023 Formula(up) and Convolution (down)

This analysis assesses whether computed reserves adequately cover hourly system imbalances. Both methods ensure sufficient upward reserves, effectively containing imbalances. However, occasional shortfalls in downward reserves are observed, with extreme imbalances below -10,000 MW during solar overgeneration.

3.2 BESS Contribution to Reserve Requirement

This section evaluates the ability of BESS to support system reserve requirements after its time-shifting operation. Using the 2030 price-driven dispatch and SoC profile, the analysis distinguishes between upward and downward contributions while considering technical constraints. Figure 6 compares hourly system reserve needs with BESS availability, showing consistently higher availability for downward reserves as compared to upward reserves. But upon calculating the contribution rather than mere availability, out of 8760 hours, BESS contributed to upward reserves in 4397 hours (50%) and downward in 6890 hours (79%). It fully satisfied upward needs in 3495 hours (40%) and downward in 5930 hours (68%).

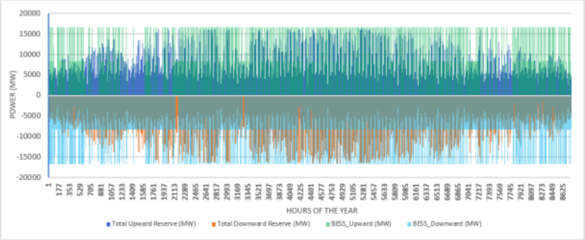

Figure 6. BESS availability and hourly reserve requirement profile – 2030

Figure 7 compares the system reserve requirement with the portion covered by BESS, distinguishing between upward and downward directions. The upward reserve not covered by BESS appears regularly, especially in the early and mid-year, due to SoC or discharge limits. For downward reserves, tall spikes remain unmet during high curtailment periods, but the overall coverage is higher and more consistent. Unmet reserves are more common in winter and summer, while spring and autumn show better coverage. It is important to understand that he reserve profiles represent theoretical needs under extreme uncertainty, and actual activation in practice is often much lower, making this a conservative estimation [3].

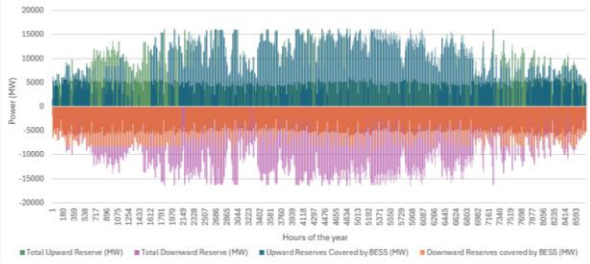

Figure 7. BESS Contribution to upward and downward reserves

3.3 Monthly Analysis

Figure 8 presents the monthly BESS contribution to upward and downward reserves. BESS consistently contributes more to downward reserves, exceeding 65% participation in all months. In months like February, March, and November, the downward reserve contribution reaches over 87%, with satisfaction above 70%, driven by high prices that promote discharging and enable charging flexibility. Upward reserve contribution is more variable and generally lower, relying on prior charging to maintain high SoC. It peaks in October, December, and June with around 62–65% contribution. Summer months show relatively stable upward reserve availability due to increased RES and more frequent charging events.

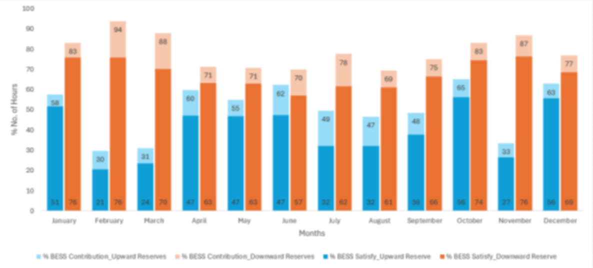

Figure 8. Monthly Analysis of BESS contribution to reserves

3.4 Weekend vs Weekday Analysis

Figure 9 compares BESS reserve participation between weekdays and weekends. On weekdays, BESS contributes to upward reserves 52% of the time and satisfies demand 41%, while downward contribution and satisfaction reach 79% and 67%, respectively. During weekends, upward contribution and satisfaction drop slightly to 45% and 37%, while downward values remain high at 78% and 70%. The difference is attributed to weekday load peaks and more frequent price variations, enhancing operational flexibility

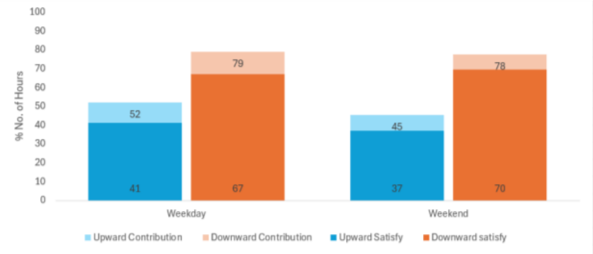

Figure 9. Weekend vs Weekday Analysis

3.5 Economic Analysis

This section evaluates the total reserve energy demand and associated economic costs for 2030. Upward reserves are projected to rise from 41.48 TWh (2023) to 51.41 TWh, while downward reserves increase from 33.28 TWh to 54.07 TWh. The corresponding costs are €90.48 million for upward and €95.16 million for downward reserves, based on a capacity price of €1.76/MW/h. Italy is transitioning to a dual-payment scheme (TIDE), aligning with EU practices [12]. BESS is modeled to cover 58% of reserves, equating to 2.65 TWh of the expected 5.3 TWh activated volume in 2030. Applying split LCOS (€25/MWh), the estimated BESS reserve provision cost is €66.25 million. This reflects the role of BESS as a reliable and cost-effective flexibility provider under rising renewable penetration.

4. Conclusions

This study assesses reserve estimation methods for Italy's 2030 power system, focusing on challenges from high renewable penetration. Using both formula and convolution methods, the formula-based approach estimated a 20% rise in upward and 38% rise in downward reserves, while the convolution method showed lower increases. Given its conservative reliability, the formula-based approach was selected as the basis for BESS dispatch and economic modeling. A system-level BESS model was implemented to assess its technical and economic role in meeting future reserve needs. The model demonstrated that BESS could contribute more than 50% of upward and nearly 80% of downward reserve hours. By absorbing excess energy and supporting peak demand, BESS reduces the reliance on conventional thermal units and mitigates the risk of curtailment. Economically a refined estimation method was used to evaluate the cost of BESS-based reserve provision. Assuming a 5% activation rate, BESS is expected to deliver approximately 2.65 TWh of reserve energy in 2030. Applying a split LCOS of €25/MWh (considering both upward and downward services), the estimated cost amounts to €66.25 million. From a regulatory and planning perspective, this work provides valuable inputs for future ancillary service market design, including sizing BESS for reserve provision, evaluating compensation schemes under frameworks like TIDE, and encouraging availability-based remuneration

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