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Strategic Solutions to Address the Challenges and Impacts of Renewable Energy Growth on Italy's Transmission Network

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Abstract

With the ongoing decarbonization of energy systems, the share of renewable energy sources (RES) is rapidly increasing, posing significant challenges for Transmission Power Systems to be operated while maintaining their adequacy and security. This thesis analyzes the main impacts and challenges posed by the new RES plants and the concrete solutions currently implemented by the Italian Transmission System Operator (TSO). The aim of this study is to analyze how the Italian transmission grid will evolve in the medium term due to the increasing penetration of renewable energy. Simulations are performed using the calculation software WinCreso, where newly authorized renewable energy plants scheduled to be operational by 2025 were modeled. The goal of these simulations is to identify which sections of the grid will experience the highest stress due to the increased renewable energy generation, and to determine the most critical congestioned areas. Furthermore, the simulations aimed to highlight which interventions are most urgent and necessary to ensure the safe and efficient operation of the Italian transmission network. An in-depth analysis was conducted for a portion of Center-South Italy, incorporating specific assumptions regarding renewable energy production to better model the substantial increase in RES plants expected in this area.

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Chapter 1

Introduction to Current Status, Future Requests and Policies for Renewable Energy Grid Integration in Italy

1.1 European Union Energy Transition Policies and Goals

Making the energy systems more sustainable is currently a global need. Therefore the necessity of a decarbonization process is crucial and can lead to a reduction of both the Greenhouse Gases (GHG), in particular CO_2, with a significant negative impact in the global warming, and air pollutants which represents an issue for human health. Increasing the penetration in the energy mix of Renewable Energy Sources (RES) and developing a transmission network capable to support their fast growth are key factors to implement the energy transition, and can be positive not only for the environment but also for the security of supply, since could allow to reduce energy imports from other countries.

In July 2021, the European Commission adopted the legislative package "Fit-for-55" (FF55), which aims to reduce CO_2 emissions at the European level by 55% compared to 1990 levels by 2030 and to achieve climate neutrality ("Net Zero") by 2050, in line with the European Green Deal. [1] [2] [3]

According to the "Fit-for-55" package the target for Italy is 65% of electricity produced from RES in the gross electricity consumption in 2030, that can be translated into the need of 70 GW of new RES installations. Among these 70 GW, about 15 GW will be wind power and 55 GW will be solar photovoltaic, in particular 42 GW of the 55 GW of photovoltaic will be represented by utility-scale plants.[3] On the basis of the connection requests received by Terna, the Italian Transmission System Operator (TSO), it can be said that the majority of the new RES quotas, 50 GW, will be installed in the South of Italy and in the Islands (Sardinia and Sicily), and mainly consist of utility-scale photovoltaic plants, onshore wind power and offshore wind power (near the Islands). On the other hand, in the North and Centre-North only 20 GW will be installed, largely represented by small-scale photovoltaic plants.[3]

This will result in a more exasperated situation in which the electricity production from RES is located for the most part in the South of Italy, far from to the zones in the North where the higher consumption occur, causing a further increase of the electricity flow from the South to the North. In its current state of development the Italian Transmission Network could not guarantee a sufficient transmission capacity between the Market Zones and especially from South to North, resulting in the necessity of curtailment of the RES generations and the need of other energy sources, typically fossil fuels such as natural gas. Hence the Italian Transmission Network will call for significant infrastructural works to adapt its transmission capacity as a function of the location of the RES plants, in order to reduce the technical limitations to the integration of new RES quotas in the energy mix.

1.2 Renewable Energy Deployment in Italy: Current Status

To provide an overview of how the total installed capacity in Italy is distributed among different sources, the situation at the end of 2023 is taken as an example. As of December 31, 2023, the total installed capacity in Italy amounted to 137 GW. Figure 1.1 shows the breakdown of this capacity across various types of plants. The two main RES, wind and photovoltaic, accounted for 12 GW (9% of the total) and 30 GW (22%), respectively, making up 31% of the total installed capacity.

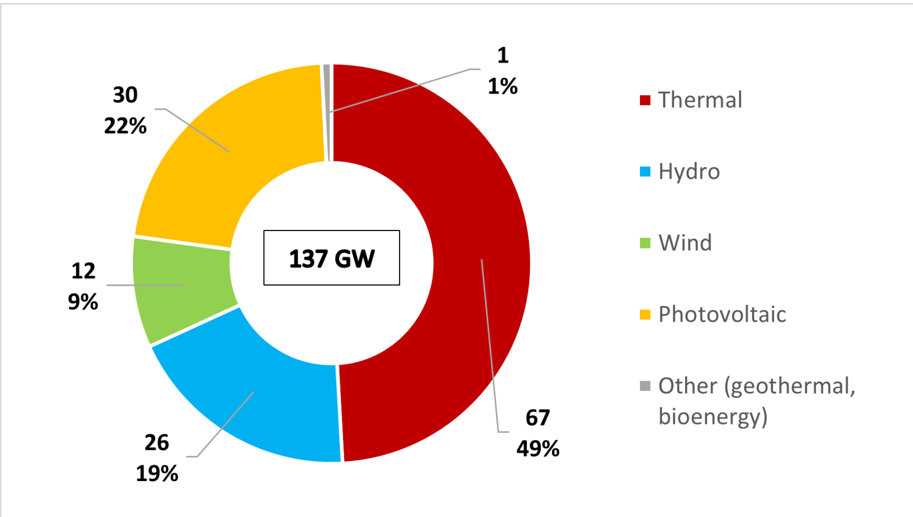


Figure 1.1: Installed capacity by source as of December 31, 2023. [Source: Terna]

In recent years, there has been a significant increase in new capacity installations, with the vast majority coming from new photovoltaic plants and a smaller portion from wind power plants. Most of the newly installed photovoltaic plants have a capacity of less than 12 kW, with an average size of around 6 kW. Conversely, the majority of new wind power plants have a capacity of over 10 MW. Thermal capacity, however, has remained almost unchanged. The decommissioning of some thermal plants has been offset by minor repowering efforts on others. Therefore, it can be said that increases in RES now represent the most significant changes in the country's total installed capacity. Notably, the rate of RES installations has been higher compared to the average trend of 800 MW per year recorded in previous years [3].

More in detail, table 1.1 presents the installed capacities for each year from 2021 to September 2024, highlighting the annual variations compared to the previous year's capacities.

Year	**Photovoltaic [GW]**	% increment	**Wind [GW]**	% increment
2021	23.6	-	11.4	-
2022	26.1	10%	12	3%
2023	31.0	14%	12.4	3%
September 2024	35.2	19%	12.8	5%

Table 1.1: Installed capacity and percentage increments of wind and photovoltaic in Italy from 2021 to September 2024. [Source: Terna]

Following the increase in RES installations in recent years, the status of installed renewable energy sources in Italy as of September 2024 is presented below. The photovoltaic and wind installed capacities are currently 35.2 GW and 12.8 GW, respectively. Tables 1.2 and 1.3 display the shares of installed capacity at LV, MV, and HV levels, along with the respective percentages of total capacity for photovoltaic and wind power based on the September 2024 data.

PHOTOVOLTAIC PLANTS				
	Installed capacity [MW]	% of the total	**N° of plants**	% of the total
LV	14785	42%	1787810	98%
MV	17316	49%	34595	2%
HV	3043	9%	202	0%
TOT	**35,144 MW**	100%	**1,822,607**	100%

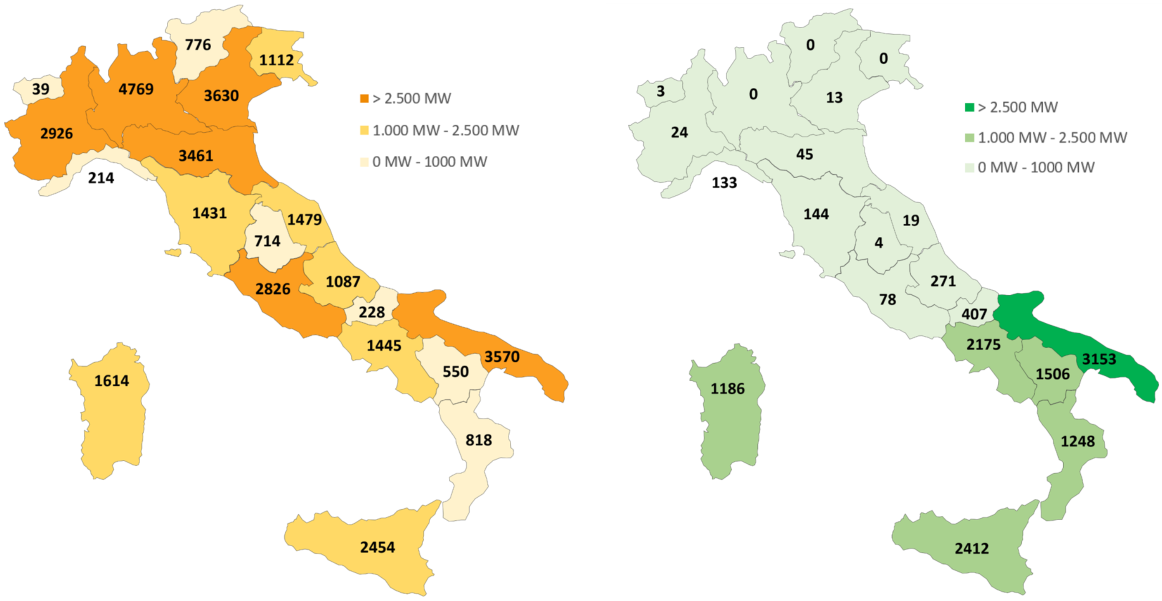
Table 1.2: Shares of installed capacity at LV, MV and HV levels, and respective percentages of total capacity for photovoltaic energy as of September 2024. [Source: Terna]

WIND PLANTS				
	Installed capacity [MW]	% of the total	**N° of plants**	% of the total
LV	238	2%	4880	80%
MV	1008	8%	826	13%
HV	11576	90%	815	7%
TOT	**12,822 MW**	100%	**6,121**	100%

Table 1.3: Shares of installed capacity at LV, MV and HV levels, and respective percentages of total capacity for wind energy as of September 2024. [Source: Terna]

The majority of the installed capacity for most sources, including wind, is connected to high voltage (HV). However, solar power is an exception; instead of following this trend, only the 9% of its total installed capacity at the moment is connected to HV, with the majority being connected to medium (MV) and low (LV) voltage levels.

In general, the geographical distribution of photovoltaic plants is fairly uniform across Italy, both for connections to HV and to MV and LV. This distribution is not directly related to the solar resource, which is more abundant in the South. The pattern reflects an installation strategy driven more by private economic interests rather than by optimizing production. It is interesting to notice that, certain areas, such as the Po Valley and the province of Rome, have a high number of plants connected to MV and LV, but with lower installed capacities compared to regions like Puglia and Calabria, where there are fewer plants but with higher capacities. In contrast, the geographical distribution of wind power plants is closely aligned with regions that have higher wind availability, typically found in the South, particularly in the province of Foggia (Puglia). In figure 1.2 the distribution of photovoltaic and wind installed capacity among Italian regions as of September 2024 are shown.



(a) Photovoltaic installed capacity [MW]. (b) Wind installed capacity [MW].

Figure 1.2: Geographical distribution of photovoltaic and wind installed capacity as of September 2024. [Source: Terna]

1.2.1 Energy balances

Regarding energy balances, RES covered 40% of national electricity production in 2021 and 31% in 2022. This change is attributed to increased wind and photovoltaic installations, but also to a reduction in hydroelectric generation, which historically provides the primary contribution to RES. Between 2021 and 2022, wind and photovoltaic production increased by +6%, while hydroelectric production decreased by -38%. Considering also the exchanges with other countries, the RES share of Italian electricity consumption amounted to 35% in 2021 and 31% in 2022. [3]

In 2023, thermal power generation decreased by 20.4% compared to 2022, while hydroelectric power grew by 34.1% from the previous year, a significant increase attributed to the fact that 2022 had been a drought year. Wind power increased by 14.8%, and solar power production by 8.8%, driven by the expansion of installed capacity, resulting in the 41% of the electricity production.

In the first half of 2024, there was a significant increase in renewable energy production (+27.3%) compared to the first half of 2023, primarily driven by hydroelectric power (+64.8%) and an increase in solar and wind energy by +14.6%. For the first time, renewable energy production surpassed fossil fuel production, which decreased by 19% compared to the same period in 2023. Additionally, from January to June 2024, hydroelectric power production reached a record high of 25.92 TWh, marking a 64.8% increase from the 15.73 TWh recorded in the first half of 2023. Renewable sources covered 43.8% of energy demand in the first half of 2024, compared to 34.9% in the first half of 2023, setting a new historical record on a semi-annual basis. On June 22, between 1:00 PM and 2:00 PM, the highest hourly production from renewable energy sources was recorded at 33.2 GW. [Source: Terna]

1.3 Connection Requests for new RES Plants Submitted to Terna

The monitoring and the analysis of the new connection requests are strategical actions for Terna in order to efficiently develop the electrical infrastructure to achieve the "Fit for 55" target at 2030. Terna must provide a solution for the grid connection to all those who request it. After the user request, Terna provides a *STMG (Soluzione Tecnica Minima Generale)*, which is a preliminary and general solution that includes the costs and the timing for the necessary interventions on the transmission grid. If the user accept this solution it has to submit its project, which includes the *STMG*, to the public administration in order to obtain the authorization. When the user has obtained the authorization Terna provides a *STMD (Soluzione Tecnica Minima di Dettaglio)*, which is a detailed grid connection solution, then a contract is stipulated between the TSO and the user and the realization of the plant can start. [3]

The total of the connection requests in Italy amounts to 341.33 GW on the 30th of June 2024 and it is partitioned among different types of RES as shown in table 1.4.

	Requested connection capacity [GW]	**% of the total**
Photovoltaic	150.29	44.03%
Onshore wind	106.74	31.27%
Offshore wind	84.30	24.70%
TOTAL	**341.33**	100%

Table 1.4: Requested connection capacity by source at June 2024.[4]

In figures 1.3, 1.4 and 1.5 the detail of how the connection requests for the three main RES are distributed among the Italian regions can be seen. It is clear that the most of the requests are in the South regions and in the Islands, where already now there are the more significant RES quotas. Hence the need to transport the electricity from the South to the North, where most of the loads are placed, will be exasperated in the future.

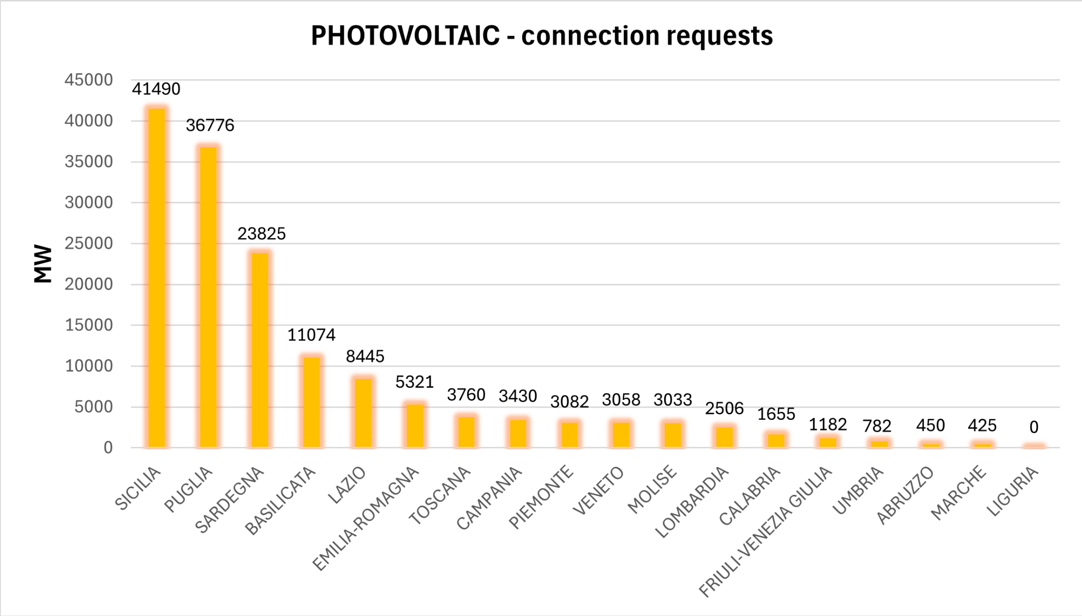


Figure 1.3: Distribution of photovoltaic connection requests to HV grid among Italian regions.[4]

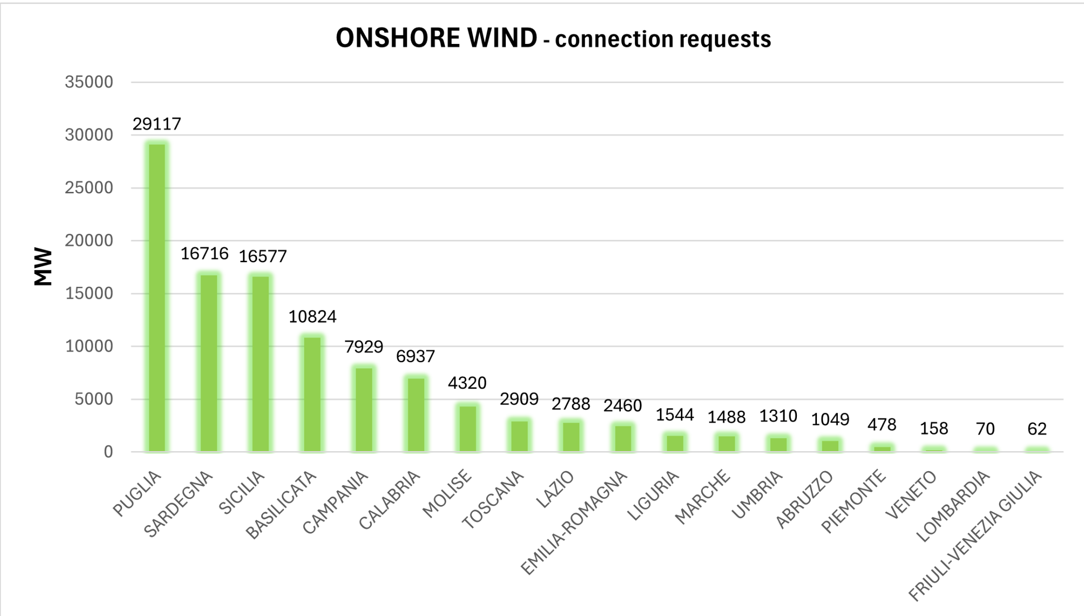


Figure 1.4: Distribution of onshore wind connection requests to HV grid among Italian regions.[4]

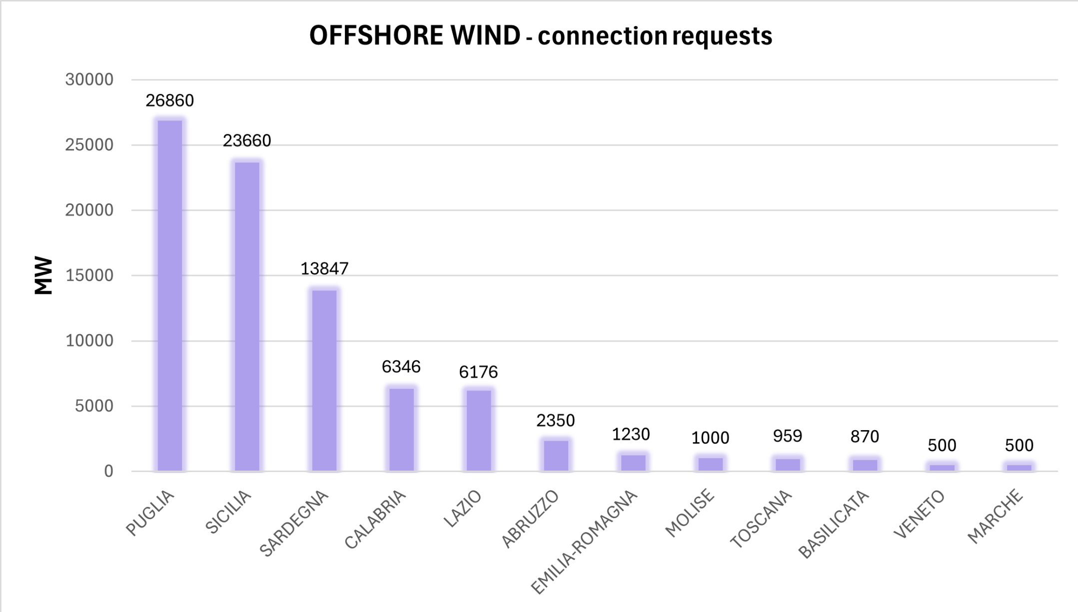


Figure 1.5: Distribution of offshore wind connection requests to HV grid among Italian regions.[4]

To illustrate this concept, figure 1.6 shows the total capacity of connection requests for photovoltaic, onshore wind, and offshore wind, distributed across Italian regions. Puglia, Sicilia and Sardegna are in order the three regions with the higher connection requests capacity of RES. In figure 1.7 the geographical concentration can be easily seen.

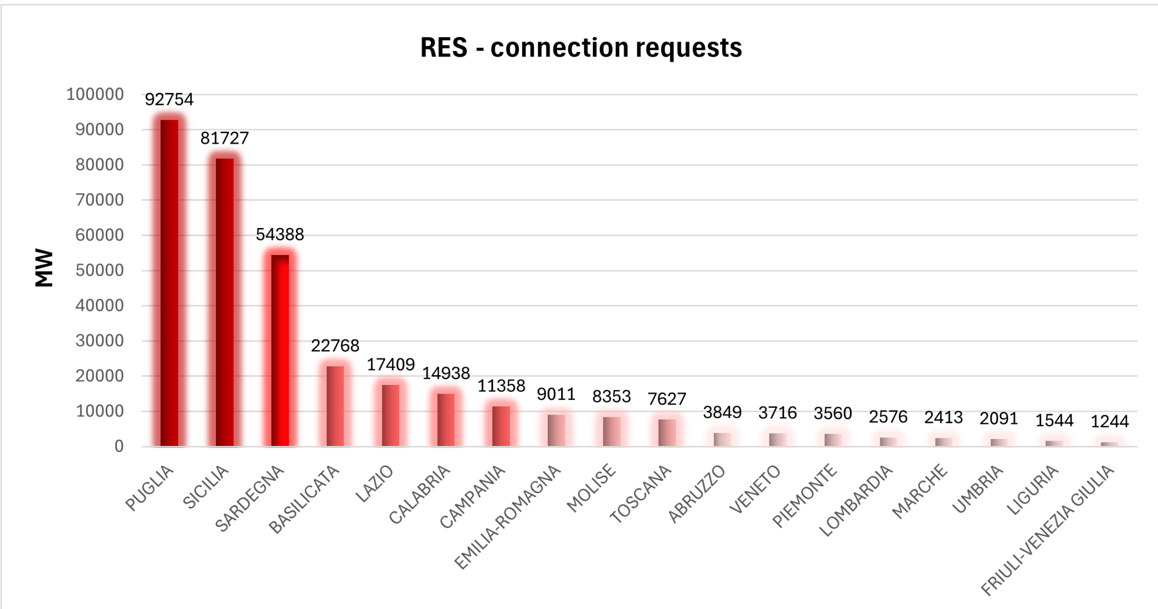


Figure 1.6: Distribution of photovoltaic, onshore and offshore wind connection requests among Italian regions.[4]

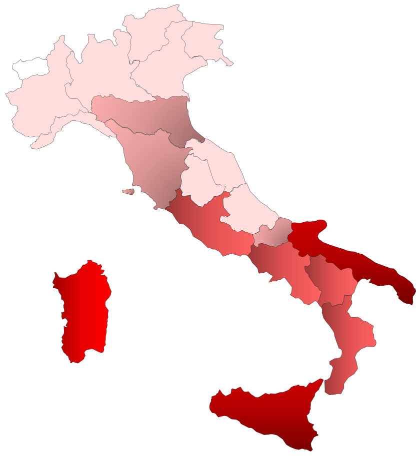


Figure 1.7: Map of the distribution of photovoltaic, onshore and offshore wind connection requests among Italian regions.[4]

To date, the connection requests for new RES plants are well above the ones needed to reach FF55 targets, especially in the South, in Sicilia and in Sardegna . In particular the target is to install 69.89 GW of new RES by 2030, thus the 341.33 GW of new connection requests represents the 488% of the needed new capacity. Moreover their geographical distributions is different from the one foreshadowed by the FF55 scenario, therefore more infrastructural works to adapt the transmission network to the location of the new RES plants will be required. In figure 1.8 the difference between the connection requests and the FF55 targets can be seen for each Market Zone of Italy. However, it should be noted that, based on previous years, not all plants that submit a connection request are ultimately realized.

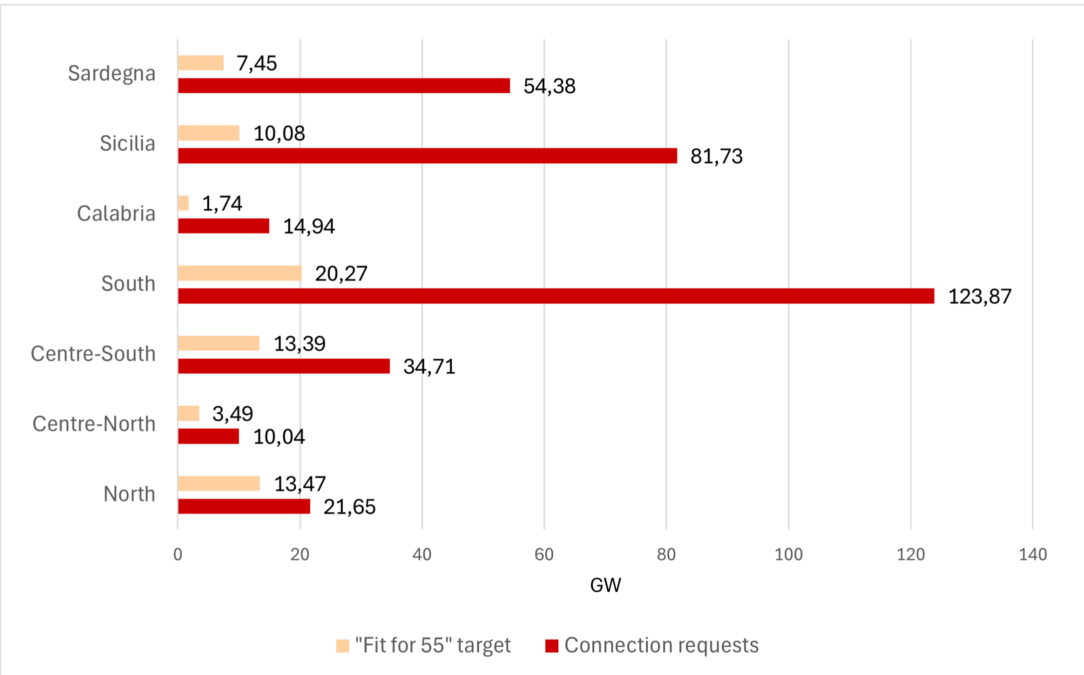


Figure 1.8: Connection requests capacity compared to FF55 target for each Market Zone of Italy.[4]

1.4 Connection Requests for new Data Centers Submitted to Terna

Today all over the world the ability to properly manage and use data is of crucial importance for every kind of business, just think of the different applications of the Artificial Intelligence (AI) or the IoT (Internet of Things). As a consequence, the presence of big, efficient and performing infrastructures to manage ICT processes and data are of crucial importance for the economic competitiveness of each country. Data Centers (DC) are infrastructures for the execution of ICT processes, processing and storage of data, also for third parties. In Europe several investments have already been made for many years, while in Italy this sector is growing from the last three years. Nowadays in Italy there are 190 DC, placed in the North and in the Centre, but they are mainly connected to the MV grid because of their limited size.

The current trend is to build bigger DC aggregated in new technological hub that allow the sharing of the infrastructures among different companies. The size of these new DC will be between 10 MW and 200 MW with an average size of 80 MW, and therefore they will be connected to the HV grid. Their electricity consumption is due to the power required for computational processing, which is the biggest consumption, cooling systems and safety equipment. [Source: Terna]

The connection requests submitted to Terna for new DC is around 2 GW and the 80% is in Lombardia. This region is already characterized by the highest electricity demand in Italy: in 2023 the demand in Lombardia amounted to the 21% of the Italian demand. Moreover in this region there is the higher number of potential customers because of the presence of big industries. Indeed, among the main drivers to select the location of a new DC there are the telecommunications quality, electricity infrastructures quality and the proximity to the users. [3] [Source: Terna]

Chapter 2

Issues in Managing the Transmission Grid with Rising Renewable Energy Penetration

An increasing penetration of RES quotas in the total installed capacity will significantly impact the management of the transmission grid, particularly in terms of robustness, stability and quality of service. The main impacts on the electricity system are listed below, and they are due to the localization of the RES, their intrinsic characteristics, and their non-programmability. The following sections outline some concrete solutions currently being implemented by Terna to manage and develop the Italian transmission grid.

2.1 Over-generation from RES in the peak daylight hours

The RES production follows the availability of the source, and while the wind production is almost independent from the hours of the day, the photovoltaic production is absent during the night and is higher in the central part of the day. This cause an over-generation during the central hours of the day and a steep increase of the residual load in the evening. The residual load is defined as the difference between the total load and the RES production, hence it is the amount of the load that has to be covered with programmable plants.During days with high RES production, and in particular high photovoltaic production, the residual load varies significantly throughout the day and has a steep increase in the evening due to the decreasing photovoltaic production and the increasing load. In this way, the residual load curve takes on the characteristic shape known as the "duck curve." This situation is more critical as the amount of RES installed capacity is increased.

In figure 2.1 the load, the breakdown of energy production and the foreign exchanges are shown for Sunday 5th of May 2024. It can be clearly seen how in the central part of the day almost the total of the load is covered by RES production, in particular by photovoltaic plants. In figure 2.2 the residual load is reported for the same day and it can be noticed how steep is its increase after 5 PM.

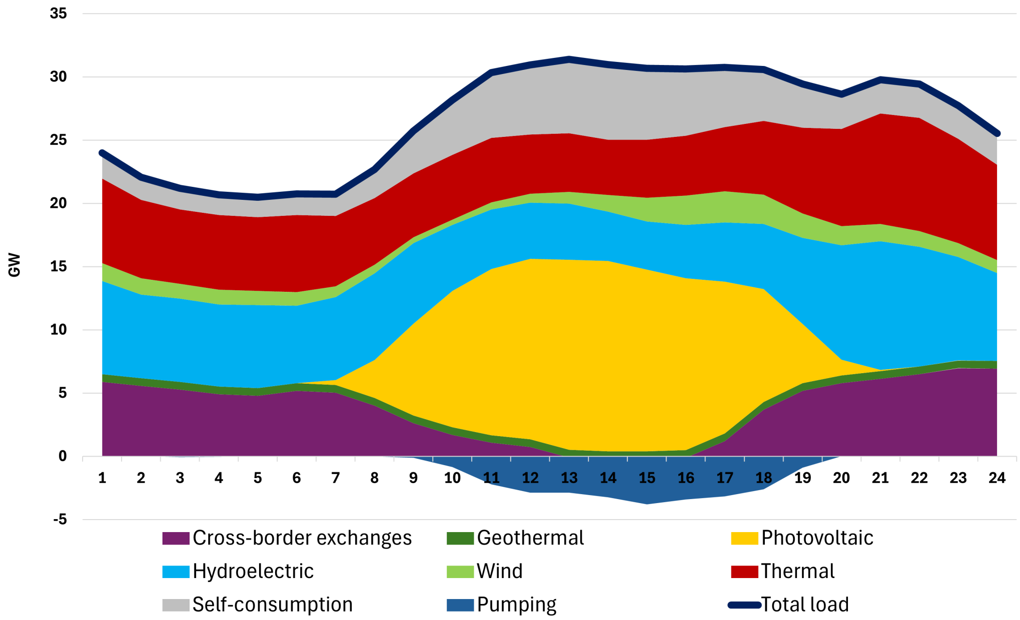


Figure 2.1: Total load, breakdown of energy production and foreign exchanges for the 5th of May 2024. [Source: Terna]

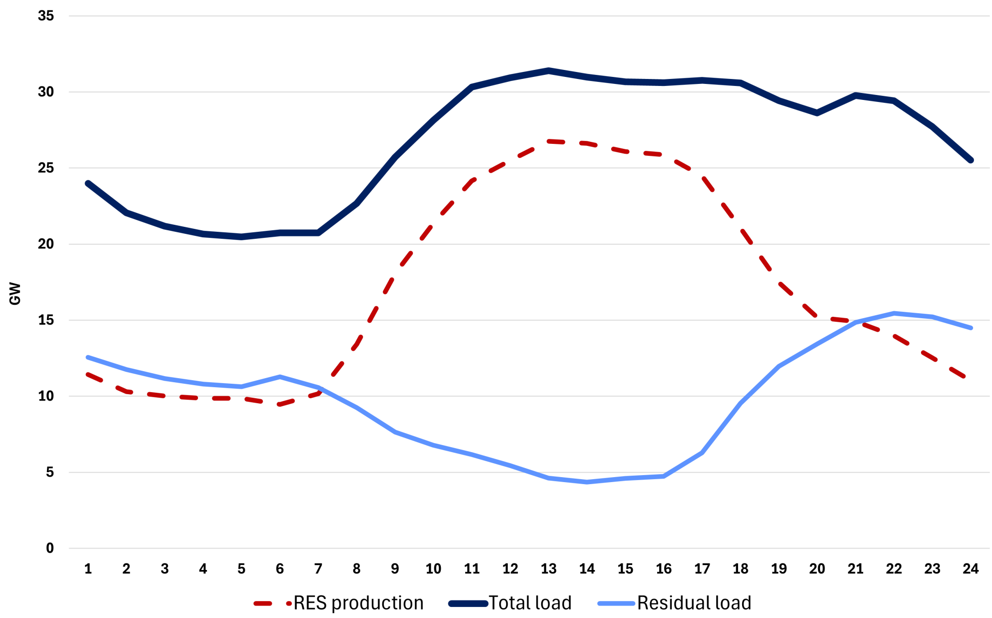


Figure 2.2: Residual load and RES generation for the 5th of May 2024. [5]

2.1.1 Storage and pumping strategies

In this scenario, storages and hydroelectric pumping play a fundamental role. They can provide a load shifting by being charged during the over-generation periods and discharged in the evening when the residual load is higher. The storages can be divided into:

- **small-scale**, typically electrochemical batteries with an energy to power ratio of 4 hours which can be installed together with small size RES plants in order to increase the self-consumption;
- **utility-scale**, hydroelectric pumping or electrochemical batteries with an energy to power ratio of 6-8 hours, in order to store high quantity of energy and have an high amount of power available. [3]

In this context, two additional definitions are necessary: nominal power, which is the active power the storage system can provide during the discharging phase, and maximum utilized capacity, which refers to the highest amount of energy that can be extracted from the storage.

In September 2024 the installed storage plants accounts to 692,386 : the total nominal power is 5,034.1 MW and the maximum utilized capacity is 11,387.7 MWh. The utility-scale plants are connected to the HV grid and therefore can be controlled by Terna, while usually the small-scale storages are connected to MV or LV grid. [3] In table 2.1 there is the detail of how the installed storage plants are divided among the different voltage levels.

INSTALLED STORAGE PLANTS				
	N° of plants	% of the total	**Nominal power [MW]**	% of the total
LV	691938	99.935%	4168,3	83%
MV	426	0.062%	54,32	1%
HV	22	0.003%	811,47	16%
TOT	**692,386**	100%	**5,034.1**	100%

Table 2.1: Shares of installed storage plants at LV, MV and HV levels, and respective percentages of the nominal power and of the maximum utilized capacity as of September 2024. [Source: Terna]

For what concern the hydroelectric pumping in 2023 in Italy there were 22 plants, with a maximum power in absorption (charging phase) of 6.5 GW and a maximum power in production (discharging phase) of 7.6 GW. The majority of them is in the North and this is a limitation for their use to mitigate the issue of the RES over-generation. [3]

During the operation of storage systems and pumping stations, it is crucial to carefully plan the charging and discharging phases. The storage systems, or the upper reservoir in the case of a hydroelectric pumping plant, must be discharged at the appropriate time to ensure they can be recharged when over-generation occurs.

2.2 Grid congestion

A grid congestion is defined in the Italian Grid Code [6] as a "situation of operation, even potentially, of an electrical network characterized by deficiencies in electricity transmission service due to network constraints", such as the lines' maximum current thresholds. The present Italian energy scenario is characterized by rapid growth in RES quotas, especially in the South and on the Islands, where the majority of connection requests, both onshore and offshore, are concentrated. Meanwhile, projections for load evolution highlight an increase in the North, particularly due to the new data centers. This will increase the need for electricity flows from South to North, which also means a need to enhance the transfer capacity between regions and market zones. In fact, in 2022, there were 690 hours of congestion between the South and Centre-South and 1290 hours between Centre-South and Centre-North. If the FF55 target for new RES installations is met but no grid improvements are made, these congestion hours are projected to increase to 3800 and 3200 hours, respectively, by 2030. [3]

2.2.1 Intentional Radialization and Mesh Loss in Network Operation (*Antennizzazione*)

The transmission network is typically operated in a meshed configuration. Due to this inherent structure, the power flow on one line also impacts the flow on other lines connected to the same busbars. In the context of the Italian transmission network, this means that when power flows through a 380 kV line connecting two busbars, a portion of this power is redistributed across other 220, 150, or 132 kV lines that follow a similar path or are connected to the same busbars. This redistribution can lead to congestion on these lower-voltage lines (220, 150, or 132 kV), especially since they are often connected to RES plants. These lines must handle both the redistributed power from the 380 kV lines and the output from the RES plants.

To manage this issue, Terna occasionally opts to open certain circuit breakers on the 220, 150, or 132 kV lines, thereby converting the meshed configuration into a radial one. In a radial configuration, the power flow on the 380 kV line no longer affects the lower-voltage lines, as opening the circuit breakers effectively disconnects the path between the two busbars, leaving the 380 kV line as the sole connection. Consequently, the lower-voltage lines are relieved from the risk of congestion, needing only to handle the RES power. In such cases, the generators, or any connected loads, are said to be connected "*in antenna*". However, in a radial configuration, the quality of service may be compromised, as the risk of interruptions increases.

2.2.2 Curtailment of RES production

An extreme strategy employed by Terna to address network congestion and bring the transmission grid back within safe limits is the curtailment of production from renewable energy sources. The reduction in RES production, both wind (*MPE - Mancata produzione eolica*) and solar (*MPS - Mancata produzione solare*), indicates the amount of MWh of energy that was not generated due to the need for production modulation. The curtailment of RES production can be necessary also for other reasons such as dynamic stability or respect of voltage limits.

In 2023, total wind curtailment amounted to 295 GWh. Under N conditions, 4.8 GWh were attributable to congestion in the primary network (380 kV), and 53 GWh to congestion in the sub-transmission network (220 kV, 150 kV, and 132 kV). Under N-1 conditions, 24 GWh were attributable to congestion in the primary network, and 102 GWh to congestion in the sub-transmission network. Thus, curtailment due to congestion accounted for approximately 60% of the total wind curtailment. Notably, there was a significant increase in the proportion of annual curtailment due to congestion compared to 2022. The majority of wind curtailment due to congestion occurred in Puglia and Campania, particularly in the Benevento area. Other regions with significant wind curtailment include Basilicata, Sardinia, and Sicily. Table 2.2 shows the wind curtailment in 2023 due to congestion in the line corridors that face the greatest congestion issues. The results are reported both for the N condition and for the N-1 condition.

Line corridors facing congestion issues	**N condition**	**N-1 condition**
Basilicata area	2.7 GWh	22.1 GWh
Campania area	45.5 GWh	21.4 GWh
Puglia area	0.6 GWh	24.5 GWh

Table 2.2: Wind curtailment [GWh] due to congestion in the line corridors that face the greatest congestion issues in 2023. [Source: Terna]

Regarding solar curtailment, it totaled 3.6 GWh in 2023, with 8% attributed to network congestion. This indicates that curtailment to address network congestion is more commonly applied to wind installations. About 40% of solar curtailment occurred in Sardinia, while other regions with notable solar curtailment include Abruzzo, Lazio, and Sicily.

2.2.3 Remote Disconnection of Generation (*Telescatto*)

Terna uses a centralized defense and monitoring system (*SCDM - Sistema Centralizzato di Difesa e Monitoraggio*), designed to centrally control multiple defense subsystems, each tailored to a specific task. The *SCDM* allows for the integrated management of various defense logics simultaneously, coordinated interaction with other systems (such as SCADA, command and control systems, WAMS, DSA), rapid response to events, and a unified human-machine interface for Control Room operators. Among the systems with which the *SCDM* communicates are the remote disconnection systems (*telescatti*), implemented in specific network areas where an immediate reduction in production is necessary to address fast electromechanical dynamics. This includes managing transient angle stability, rapid overloads (congestion), and voltage control. The time constant for these phenomena ranges from hundreds of milliseconds to tens of seconds. The remote disconnection logic involves direct generator disconnection and may also include instant commands on network elements (such as lines or reactors) that, based on system studies, can help mitigate the effects of the controlled contingency.

The *SCDM* system acquires the necessary information to execute defense logics from dedicated peripheral devices. These devices not only send information to the central system but also execute commands based on grid events. They include *UPDM* units (Peripheral Disconnection and Monitoring Unit), which are installed at electrical substations and production plants. The execution of remote disconnection is achieved through a two-phase process: the arming phase (preparation for action) and the execution phase of the disconnection commands. During each update cycle, typically lasting a few seconds, the *UPDM* units send to the central system the necessary signals and telemetry to determine remote disconnection interventions. Using this information, the central logics determine the arming strategies for remote disconnections, including triggering events (the tripping of a controlled element) and locations, and send signals to the relevant *UPDM* units. The triggering event is detected directly by "sentinel" *UPDM* units. When the triggering event occurs, it is no longer necessary to go through the central system: the sentinel *UPDM* itself sends a disconnection signal over the communication network to all other *UPDM* units, which execute the disconnection in less than a second. Regarding grid congestion, a slower execution mode is provided, allowing producers to collaborate with Terna's Control Rooms in managing the implementation of the reduction order. This mode ensures sufficient time for effective intervention to resolve network congestion while also allowing the producer to follow standard shutdown or production modulation procedures. [6]

Two practical examples of Terna's application of remote disconnection are the "Telescatto Benevento III" and the "Telescatto Rumianca." The "Telescatto Benevento III" is used to manage the significant wind generation in the area and ensure the secure operation in parallel of the two 380/150 kV autotransformers (AT), as well as the safe operation of the "Montefalcone - Campobasso" line corridor. If one of the two ATs trips, the wind production in the area will be remotely disconnected. The "Telescatto Rumianca" is implemented to manage the large RES production associated with the Rumianca substation. It controls the power flows on the 220 - 150 kV grid in the Rumianca - Cagliari area, and in the event of an overload on one of the lines, it remotely disconnects the RES generators. [Source: Terna]

2.2.4 Dynamic Thermal Rating (DTR)

Dynamic Thermal Rating (DTR) is a method for managing 400/220/150 kV power lines to maximize the use of the main transmission assets while respecting safety constraints. This is achieved through real-time estimation of current capacity of the lines based on varying operational conditions and environmental parameters. The system inputs include the passing current, technical parameters of the line, and environmental conditions (such as wind) obtained from weather stations and high-resolution forecasts. This information is then sent to a central server at Terna, which processes the data to optimize the current capacity of the power lines based on the actual thermo-climatic conditions for the subsequent 30 minutes. [3] [Source: Terna]

DTR allows for the use of a real-time calculated line capacity that is higher than the static rating for a significant percentage of the time. In fact, dynamic limits are often less stringent than static limits, which are defined based on particularly conservative assumptions.

Tables 2.3 and 2.4 present the distribution of DTRs installed by Terna as of the end of 2023, categorized by voltage level and geographic area.

Voltage level	**Installed DTR**
380 kV	29
220 kV	18
150/132 kV	36
60 kV	1
Total	**84**

Table 2.3: Number of lines monitored with DTR, divided by voltage level. [Source: Terna]

Area	Installed DTR
North	32
Center	18
South	24
Sicilia	10
Sardegna	-

Table 2.4: Number of lines monitored with DTR, divided by geographic area. [Source: Terna]

2.3 Frequency and Voltage Regulation: Impact on System Stability and Robustness

Security in an electrical system refers to its ability to withstand perturbations. It is the ability to react to external, natural or accidental events keeping system feasibility, therefore without violating operational limits. The key parameters that define an electrical AC system are frequency and voltage. Under normal operating conditions, these parameters remain within a range around their nominal values. [3] The Italian transmission network is part of an interconnected power system (Continental Europe) where the nominal frequency is 50 Hz. Normally, frequency oscillations with very small amplitudes, less than 10 mHz, can occur. However, in some cases, these oscillations can amplify to amplitudes in the range of hundreds of mHz, which can lead to widespread power outages. [3] During frequency transients, generators must ensure stable operation within the range of 47.5 Hz to 51.5 Hz. [6] The nominal voltage is 380 - 220 kV for Ultra High Voltage (UHV) networks and varies between 150 - 132 - 60 kV for High Voltage (HV) networks. [3]

System Stability Ensuring the secure operation of the electrical system primarily involves maintaining network stability. Stability means that the system must react immediately to sudden disturbances, preventing operational states that could lead to critical issues, such as poorly damped inter-area oscillations or frequency instability. A critical factor in maintaining stability is network inertia, which refers to the system's ability to withstand an imbalance between generation and load in the initial moments following a disturbance, preventing excessive frequency fluctuations. In a power system, any imbalance between generation and demand triggers a transient, causing changes in the kinetic energy stored in connected and operating motors and alternators, which leads to a deviation in frequency from its nominal value, with the largest amplitude of these frequency deviations occurring at the geographical extremities of the interconnected power system. Traditionally, AC network inertia is provided by conventional thermal units, such as synchronous generators and their mechanically coupled turbines, which rely on stored kinetic energy. [3] All the generation units with a nominal power above 10 MVA and specific response characteristics currently must participate to primary frequency regulation, excluding non-programmable RES. These generators on the mainland, and those in Sicilia when interconnected with the mainland, must ensure a power reserve of no less than 1.5% of their effective power, while the generators in Sardegna and those in Sicilia when not interconnected with the mainland, must ensure a power reserve of no less than 10% of their effective power. In the seconds following frequency deviation, speed regulators on the generation units participating to primary frequency regulation, automatically adjust the power output to restore the balance between generation and demand, in order to contain the frequency variation. [6] Unlike rotating generators, static generators like Inverter Based Resources (IBR), are connected to the grid through electrical devices with no moving parts. Due to this design feature, if the frequency deviates from its nominal value, IBR do not counteract the frequency variation and, in extreme cases, may disconnect from the grid if the deviation exceeds a certain threshold, further exacerbating system instability. An important indicator is the ROCOF (Rate of Change of Frequency), which shows that the time derivative of the frequency during transients increases as system inertia decreases:

$$ROCOF = \frac{df}{dt} = 50\frac{\Delta p_m - \Delta p_e}{2H} \tag{2.1}$$

where $\Delta p_m - \Delta p_e$ is an imbalance caused either by a change in the mechanical power set by the speed regulators on the generation units (Δp_m) or by a change in the electrical power consumed by the grid loads Δp_e and H, expressed in seconds, is the network inertia. [6] Therefore, as RES continue to expand, the share of thermal generation is decreasing, resulting in lower inertia and, consequently, faster and deeper frequency drops during disturbances, making the grid more vulnerable. Moreover, the decline in thermal generation has led to a decrease in the system's overall capacity for frequency regulation. [3] To overcome this issue TSOs start to install synchronous condensers or static machines such as E-STATCOMs.

System Robustness Equally important is the system's robustness, which refers to its ability to withstand voltage variations in response to disturbances (i.e., reactive power variations) at the nodes of an electrical system. [3] One of the most widely used metrics for robustness evaluation is the short-circuit power, defined as the apparent power injected into a point in the system during a fault (single-phase, phase-to-phase, or three-phase). The contribution to the short-circuit power of the IBR is much lower than the thermal generation plants and this lead to a reduction of the voltage regulation capacity. The concept of short-circuit power is directly related to robustness through the following relationship:

$$\Delta V_{i\%} = 100\frac{X_i \Delta Q_i}{3E_{oi}^3} \approx 100\frac{\Delta Q_i}{Pcc,i} = \Delta Q_{i\%} \tag{2.2}$$

where $\Delta V_{i\%}$ is the voltage variation, X_i is the short-circuit impedance at the node, ΔQ_i is the variation of the reactive power, E_{oi} is the no-load voltage and Pcc, i is the short-circuit power at the node. Based on this formula, we can say that a reduction in short-circuit power results in more abrupt voltage variations for a given change in reactive power injection into the network. Moreover, a decrease in short-circuit power in an area leads to a wider propagation of the effects of a fault across a larger region for the same fault event considered. Another aspect to consider is the reactive contribution of the lines: if they operate above their nominal power rating, they exhibit an inductive behavior, absorbing reactive power from the grid. Conversely, if they operate below their nominal power rating, they exhibit a capacitive behavior, thereby injecting reactive power into the grid. This could represent an issue, as the current development of RES may lead to a non homogeneous distribution of power flows over the the HV lines (400 kV), with some of them operating below their nominal power rating. In recent years, the issue of voltage has gained particular importance, especially during low-load hours, when the reduced number of large thermal power plants in operation decreases the regulation capacity. This exacerbates a scenario where lines carry active power significantly below their nominal power rating, potentially leading to overvoltages. [Source: Terna]

The combined effect of reduced inertia and short-circuit power, along with diminished frequency and voltage regulation capacity, poses significant challenges to maintaining grid security in an electrical system where the share of renewable energy sources is rapidly increasing.

2.3.1 Fast Reserve pilot project

Given the reduced inertia of the grid due to the high penetration of renewable energy sources, it has become necessary to implement a service that complements primary frequency regulation to maintain system stability. Recognizing this need, Terna developed and initiated a pilot project called Fast Reserve in 2020. The Fast Reserve service, in particular, is a power reserve service characterized by full activation times of no more than 1 second and activation methods that distinguish it from other types of frequency regulation services currently defined in the Italian Grid Code. For the allocation of the Fast Reserve service, downward auctions are conducted following the "pay as bid" principle. The contracts, which last five years (from January 1, 2023, to December 31, 2027), require providers to make ultra-fast frequency regulation capacity available for 1,000 hours per year in exchange for a fixed compensation awarded in the auction. Any available capacity from the selected units that exceeds the assigned capacity during the 1,000 hours of service provision can be freely offered on the Energy Markets and the Ancillary Services Market. This allows market operators to engage in "revenue stacking," meaning they can generate additional income beyond the fixed compensation for providing ultra-fast reserve services. [3]

Both physical units and virtual units, which are formed by aggregating smaller physical units, can participate in the auctions. These virtual units must collectively provide a regulation capacity of at least 5 MW but no more than 25 MW. The Fast Reserve Units are only valid for participation in the Fast Reserve pilot project and do not constitute aggregates/units for participation in the Energy Markets and/or Dispatching Services Market (*MSD*): the devices included within these units may participate in the Energy Market and (*MSD*) according to the forms and methods outlined by the current regulations. The units participating in the Fast Reserve project are defined as Fast Reserve Units (FRU) and can include the following:

- stand-alone production units (UP);
- production units that share the connection point to the public grid with one or more consumption units, excluding auxiliary services and/or storage systems ("behind the meter" UP);
- consumption units, excluding those providing the interruptibility service;
- storage systems, either stand-alone or combined with production units and/or consumption units ("behind the meter" storage systems).

Each FRU must be equipped with a frequency measurement apparatus, such as a PMU (Phasor Measurement Unit), to verify rapid frequency regulation, as well as with a *UPDM* (Peripheral Disconnection and Monitoring Unit) for remote control and integration with the centralized defense and monitoring system (*SCDM - Sistema Centralizzato di Difesa e Monitoraggio*).

Each FRU must be capable of remaining inactive until the intentional threshold for frequency error (threshold 1, default: 50 mHz) is reached. Once threshold 1 is exceeded, the FRU must provide a continuous and automatic response with power proportional to the frequency error, based on a configurable coefficient, until full activation is achieved. The activation should occur without intentional delays and within 1 second of the event triggering the service. After activation, the FRU must maintain the activated power level for at least 30 continuous seconds, and then execute a linear ramp-down to cancel the activated contribution. Instead, if the frequency error reaches threshold 2, higher than threshold 1, the response time counter resets, as the response must remain active as long as the frequency error exceeds threshold 2. The FRU must have sufficient energy capacity to consistently exchange power with the grid, at least equal to the Qualified Power (power value that the FRU is permitted to participate to the auction), both upwards and downwards, for a minimum of 15 continuous minutes. Therefore, if the frequency deviation remains above threshold 2, the activation must continue for 15 consecutive minutes. When the frequency error drops below threshold 2, the response will revert to being proportional to the frequency error, and the response time counter will restart. Upon reaching 30 seconds of response, the ramp-down process will begin and it has a default duration of 300 seconds (5 minutes). Figure 2.3 shows the power responses of a FRU in two cases with frequency error between threshold 1 and 2 at the initial instant and constant with time. [7][8]

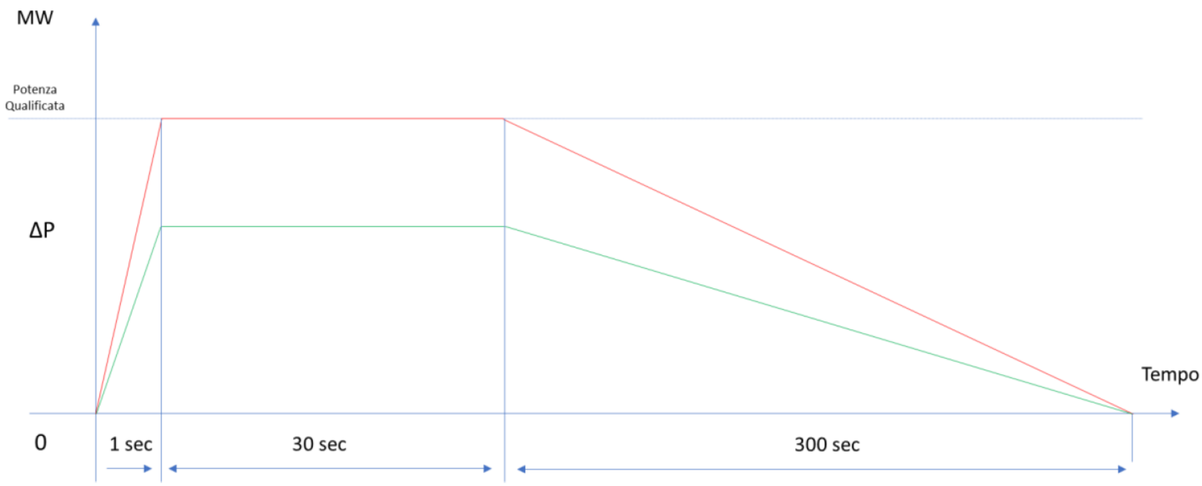


Figure 2.3: Power response of a FRU in a case with frequency error between threshold 1 and 2. [9]

2.3.2 Capacitors

Among the more traditional compensation devices are capacitor banks, which are installed on networks with a voltage of 150 kV or lower. Capacitor banks are static machines which can support voltage levels at network nodes during situations of low voltage, typically when the grid is heavily loaded, by injecting capacitive reactive power. As can be observed in table 2.5, the condensers are mainly concentrated in the more industrialized areas of Italy, which are characterized by higher consumption: about 81% of the total condensers are installed on the 132 kV network in the North and Center-North. It is important to highlight that voltage is related to the topological characteristics of the grid. Thus, capacitor banks in the more industrialized areas of the North, particularly in Lombardia, sometimes need to be activated even during periods of high voltage on the 380 kV network, such as holidays, when the maximum reactive power absorption is often required in the South. This is necessary to address low voltage levels near high loads on the 150 kV and 132 kV networks.

Voltage level	North	Center	South	Sicilia	Sardegna	Italy
380 kV	-	-	-	-	-	**-**
220 kV	-	1	-	-	2	**3**
150 kV	-	-	7	5	1	**13**
132 kV	41	27	-	-	-	**68**
Total	**41**	**28**	**7**	**5**	**3**	**84**

Table 2.5: Number and geographical distribution of installed capacitors. [Source: Terna]

2.3.3 Reactors

On the opposite side with respect to condensers, there are reactors, static machines that absorb reactive power, thereby helping to mitigate overvoltages conditions and providing a basic, discrete form of voltage regulation. These reactors are primarily installed on 220 kV and 380 kV grids, where the lines carry active power significantly below their nominal power rating in the cases when there is high RES production and fewer large thermal plants generators operating, leading to increased voltage levels. In 2023 in Italy there were 73 reactors, more than half on 380 kV nodes. Of these, the 37% is in the South (Calabria, Puglia, Basilicata e Campania), followed by the 20% installed in Lazio. Table 2.6 contains the detail of the distribution of the installed reactors in Italy.

Voltage level	North	Center	South	Sicilia	Sardegna	Italy
380 kV	9	13	15	4	-	**41**
220 kV	5	2	2	6	-	**15**
150 kV	-	2	5	2	1	**10**
132 kV	3	4	-	-	-	**7**
Total	**17**	**21**	**22**	**12**	**1**	**73**

Table 2.6: Number and geographical distribution of installed reactors. [Source: Terna]

Figure 2.4 shows the 13 reactors that are planned to be installed in the coming years until 2027. The reactors that will be installed on the 380 kV grid will have a nominal power of 258 MW, the ones that will be installed on the 220 kV grid will have a nominal power of 180 MW and the ones that will be installed on the 150/132 kV grid will have a nominal power of 60 MW or 35 MW.

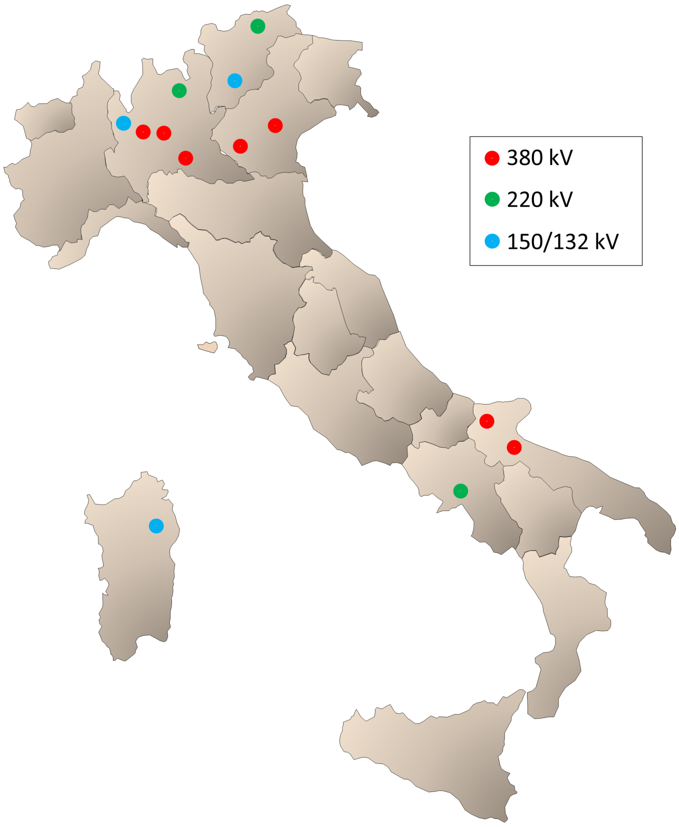


Figure 2.4: Reactors that are planned to be installed in the coming months and years. [Source: Terna]

2.3.4 Synchronous condensers

Synchronous condensers, also called synchronous capacitors or synchronous compensators, are synchronous machines capable of contributing to voltage regulation by both supplying and absorbing reactive power. Additionally, they increase the short-circuit power (Pcc) during the initial moments of faults and help counteract the frequency oscillations due to their inertia. [10] Substantially a synchronous condenser is a synchronous generator operating at zero active load. Since the zero active load operating point cannot be reached by the coupled turbine, the synchronous condenser power plant is simply an open cycle gas turbine plant where the gas turbine has been removed. One disadvantage of synchronous condensers is that, being rotating machines, they have reduced availability due to a higher frequency of failures. [Source: Terna]

The installed synchronous condensers in Italy in 2023 were 20, mostly installed on the 380 kV grid in the South, as can be seen in table 2.7. [3]

Voltage level	North	Center	South	Sicilia	Sardegna	Italy
380 kV	-	5	8	-	5	**18**
220 kV	-	-	-	2	-	**2**
Total	**-**	**5**	**8**	**2**	**5**	**20**

Table 2.7: Number and geographical distribution of installed synchronous condensers. [Source: Terna]

Figure 2.5 shows the 11 synchronous condensers that are planned to be installed in the coming years until 2031. They will be all installed on the 380 kV grid.

Figure 2.5: Synchronous condensers that are planned to be installed in the coming years. [Source: Terna]

There are two main plant configurations for synchronous condensers: stand alone package and power plants with synchronous condensing capacity.

Stand alone package

Stand alone packages are particularly useful for grid nodes where power electronics or renewable energy sources are connected.

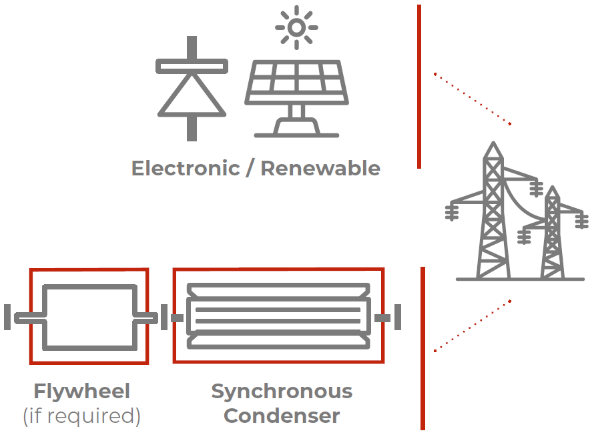


Figure 2.6: Synchronous condenser as a stand alone package. [10]

The electrical generator is installed specifically as a synchronous condenser. This package is configured by combining standard turbo generators with minor adjustments or using as alternative a fully tailored salient pole machine. An under vacuum flywheel can be supplied to provide inertia to the grid. [10] Since 2020, Terna has equipped synchronous condensers with vacuum flywheels, increasing their inertia by approximately four times compared to the standalone synchronous machine. This enhancement provides an inertia value comparable to that of a large thermal power plant. It is worth highlighting that the synchronous condensers in Matera and Selargius are the first in the world to feature vacuum flywheels synchronized with the grid. [Source: Terna]

This technology provides a minimized response time to immediately react to frequency regulation, is optimized for complete remote control, has a minimum maintenance and has a low power consumption thanks to the under vacuum flywheel. [10]

Power plants with synchronous condensing capacity

In conventional combined or open cycle plants, the turbine driven generator is decoupled from the turbine by a clutch and operated as a condenser.

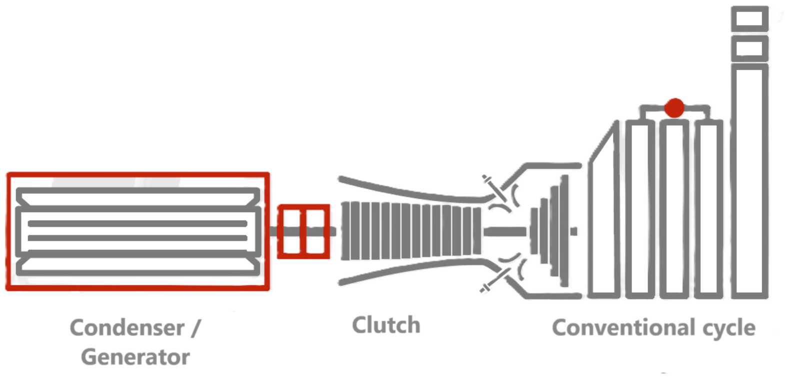


Figure 2.7: Power plants with synchronous condensing capacity. [10]

Two operating modes are possible.

- Power mode (clutch engaged): in this mode, the shaft line operates as it would in a typical power plant. The turbine drives the generator through the mechanical system. [Source: Terna]
- Synchronous condenser mode (clutch disengaged): in this mode, the clutch disengages the turbine, which is shut down, while the generator is connected to the grid, functioning as a synchronous condenser. [10] [Source: Terna]

2.3.5 STATCOM and E-STATCOM

STATCOMs (Static Synchronous Compensators) are static devices with high-performance capabilities in terms of dynamic response speed, for voltage control in the power grid by injecting and absorbing reactive power. They have primarily been employed to improve the voltage quality for industrial users. However, in recent years, due to technological advancements, they have also been increasingly used in the electric power transmission sector.

STATCOMs use Voltage Source Converters (VSCs) with insulated-gate bipolar transistors (IGBTs) power modules. In the latest generation of STATCOMs, Modular Multilevel Converter (MMC) technology is employed. The MMC contains series-connected sub-modules that generate the required AC voltage, allowing precise regulation and reducing harmonic distortion. The output waveform is nearly ideal sinusoidal, minimizing the need for filtering due to the negligible amount of harmonics generated. The IGBTs in the sub-modules are fully controllable, enabling smooth and linear variation of the output currents across the entire operating range. This feature provides superior under-voltage performance and extending support to the network at lower voltages. [11] Moreover, their response time is less than 40 ms, and the settling time is under 100 ms. [Source: Terna] In figure 2.8 the layout of a STATCOM plant can be seen.

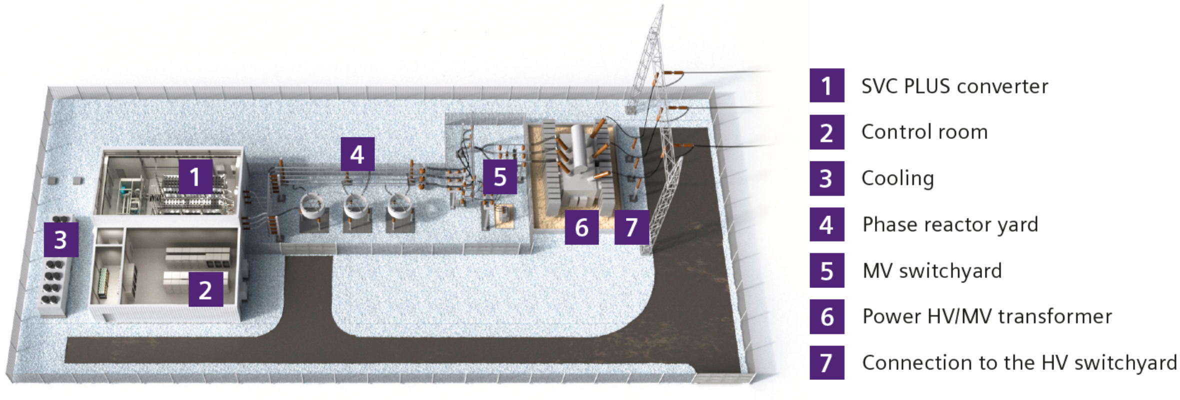


Figure 2.8: STATCOM plant layout proposed by Siemens Energy. [11]

The Extended STATCOM (E-STATCOM) is a solution that combines both voltage and frequency control in a single unit, using a bulk number of supercapacitors. E-STATCOMs consist of a STATCOM coupled on the DC side with a storage system (supercapacitors). The difference compared to standard STATCOMs lies in their contribution to inertia and short-circuit power (P_{cc}). Due to the presence of energy storage, these machines can provide an inertial response through active power injection. E-STATCOMs are a cost-effective solution thanks to their compact, space-saving design with high power density, low losses, and easy maintenance. [3] [11] In figure 2.9 a layout of an E-STATCOM plant is shown.

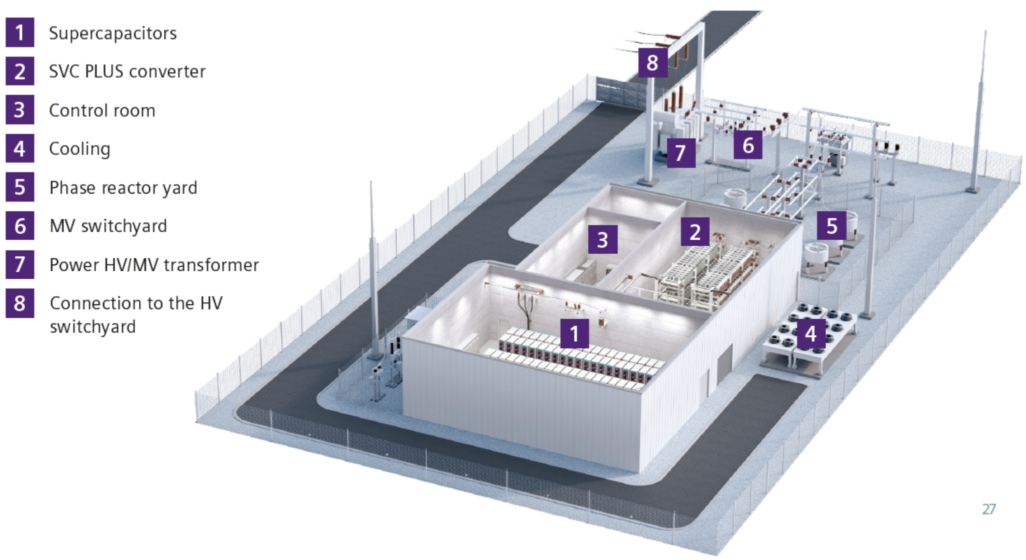


Figure 2.9: E-STATCOM plant layout proposed by Siemens Energy. [11]

The installed STATCOMs in Italy in 2023 were 5, all installed on the 380 kV grid. In table 2.8 the distribution of the installed STATCOMs in Italy can be seen. It should be noted that these systems have only started being installed by Terna in recent years.

Plant	**Region**	**Year**
Latina	Lazio	2022
Villanova	Abruzzo	2022
Galatina	Puglia	2022
Montalto	Lazio	2023
Aurelia	Lazio	2023

Table 2.8: Geographical distribution and year of installation of STATCOMs. [Source: Terna]

Figure 2.10: Geographical distribution of the installed STATCOMs. [Source: Terna]

To conclude, it is interesting to compare the capabilities that synchronous condensers, STATCOMs, and E-STATCOMs can offer for various services essential to maintaining grid stability and robustness. Table 2.9 shows this comparison in accordance with the specifications provided by leading global manufacturers. [3]

	Synchronous condenser	STATCOM	E-STATCOM
Voltage regulation	✓✓	✓✓✓	✓✓✓
Inertia	✓✓	-	✓✓✓
Short-circuit power (P_{cc})	✓✓✓	✓	✓✓
Modularity	-	✓✓✓	✓✓✓
Controllability	✓	✓✓	✓✓✓

Table 2.9: Comparison between synchronous condenser, STATCOM, and E-STATCOM. [3]

2.3.6 Stabilizing Resistors

In the interconnected Continental Europe, undamped inter-area oscillations can occur. A technology identified by Terna as a preventive measure against these frequency oscillations is the stabilizing resistor. Stabilizing resistors are static machines that can absorb active power or operate purely in reactive mode. They can be used to instantly create a stabilizing load and/or function as a distributed STATCOM. [3]

It is important to highlight that the load can significantly contribute to stabilizing and damping oscillations. Moreover, large differences in load angles between different parts of the interconnected system can promote the onset of oscillations. Another aspect to consider is the variability in the directions and paths of power flows within the system, which is increased by the growing presence of renewable energy sources.

To contribute to the damping of oscillatory phenomena, stabilizing resistor systems must include a Power Oscillation Damping (POD) device and an interface for Terna's remote system, referred to as Wide Area Damping Control (WADC). The POD function operates exclusively at the local level, while the WADC function acts at the area level, remotely coordinating the various associated plants to implement a synchronized action for damping frequency oscillations.

The solution identified by Terna is to install stabilizing resistors with a capacity of 40 MW each (the maximum active power absorption required to the resistor). The goal is to have a total installed capacity of stabilizing resistors in Italy amounting to 450–500 MW in 2026, with the target of reaching 1000 MW by 2029. [Source: Terna]

Figure 2.11 shows the 13 resistors that are planned to be installed in the coming years until 2029. All of them will be installed on the 150 kV grid.

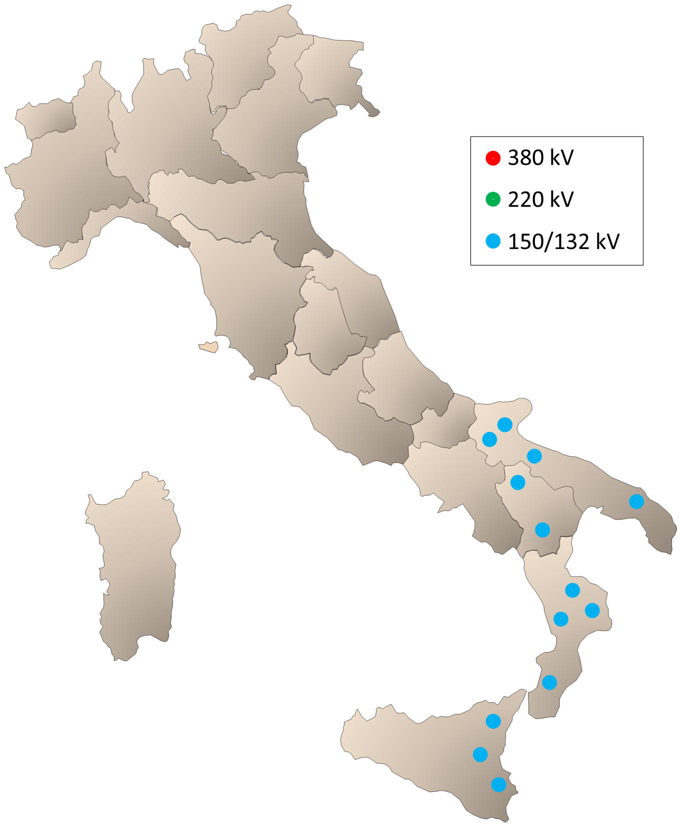


Figure 2.11: Resistors that are planned to be installed in the coming years. [Source: Terna]

2.3.7 Grid Forming

Currently, almost all inverters connected to the grid are Grid Following (GFL) type. This means that to maintain synchronization with the grid, these inverters use control techniques that primarily aim to measure the grid's voltage and frequency and create an output current waveform that is synchronous and in phase with the grid voltage at the point of connection. In electrical engineering, this behavior is defined as current source. Their operation relies on measuring the grid voltage and frequency, which introduces a delay in response and depends on the presence of the grid voltage itself. Techniques based on measuring the ROCOF (Rate of Change of Frequency) have also been developed to emulate the inertia of traditional generators with GFL inverters. However, these techniques are limited by a delay of about 150 ms, necessary to measure and process the ROCOF. In short, this control technique allows for a power response, but this response is neither instantaneous nor intrinsic, making it incomparable to inertial response.

To obtain a spontaneous and as rapid as possible response (< 5 ms), it is necessary to develop Grid Forming (GFM) control, where the conversion system connected to the plant behaves like a voltage source rather than a current source, meaning it operates as a generator that sets the voltage at its output terminals. To achieve this, the control system generates its own internal voltage and frequency curve, eliminating the need to follow those of the grid. There are several types of GFM control; for example, in the Virtual Synchronous Generator (VSG), inertial and droop equations are used to obtain a response that emulates certain physical behaviors of synchronous machines. The GFM technology also supports the process of network restoration following a blackout or the unwanted disconnection of a portion of the grid.

GFM was initially developed for managing isolated microgrids, with the idea of replacing fossil fuel plants with batteries. Recently, there has been growing interest in using GFM technology to maintain grid stability as thermal power plants are gradually being phased out. The challenge is to enable the safe operation of numerous interconnected GFM inverters. ENTSO-E recognizes Grid Forming as a crucial tool for ensuring the stable operation of future electricity systems with high levels of inverter-based generation. It urges TSOs to incorporate GFM into their grid codes to accelerate the implementation and widespread adoption of this technology across different countries. Terna aims to create a roadmap for the future management of both regulatory and technological aspects of GFM. This includes updating the Italian Grid Code to incorporate new installations equipped with GFM inverters. [3] [Source: Terna]

Principle of Operation and Operating Limits

Considering the exchange of active and reactive power between two electrically connected nodes, we can analyze the behavior of a system where node 1 represents a GFM inverter terminals, with a voltage magnitude of V_{VSG} and phase angle Θ_{VSG}, and node 2 represents the grid busbar with a voltage magnitude of V_r and phase angle Θ_r. The GFM inverter and the busbar are connected by a conductor with impedance X_{12}. When there is a variation in the phase angle or voltage magnitude on the grid side (due to a network disturbance), the active power P and reactive power Q supplied by the inverter will change accordingly. This relationship is described by the following equations:

$$P = \frac{V_{VSG} V_r \cdot \sin\left(\Theta_r - \Theta_{VSG}\right)}{X_{12}} \tag{2.3}$$

$$Q = \frac{-V_{VSG} V_r \cdot \cos\left(\Theta_r - \Theta_{VSG}\right)}{X_{12}} + \frac{V_r^2}{X_{12}} \tag{2.4}$$

To illustrate the instantaneous response capabilities and synchronization maintenance of a GFM inverter, let's consider a case of negative ROCOF, qualitatively depicted in figure 2.12. Here, t_3 is defined as the initial moment immediately following a disturbance event on the network (e.g., a generator trip).

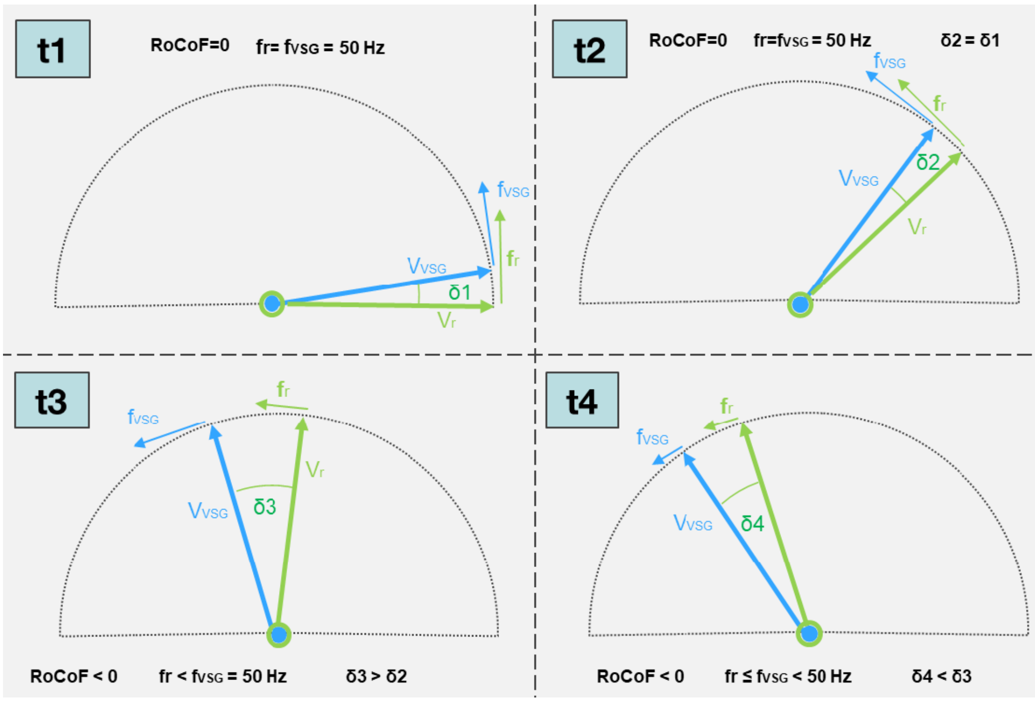


Figure 2.12: Qualitative description of instantaneous response capabilities and synchronization of a GFM inverter. [Source: Terna]

Under normal conditions, the inverter frequency (f_{VSG}) matches the grid frequency (f_r), and the angle (δ) between the voltage set by the inverter at its terminals (V_{VSG}), based on an internal set point, and the grid voltage (V_r) remains constant over time. When a disturbance occurs on the network, at t_3, a GFM inverter detects an increase in the angle between (V_{VSG}) and (V_r) because the grid begins to slow down ($\delta_3 > \delta_2$). As the grid slows, the frequency becomes $f_r < 50Hz$. The VSG inverter has not yet measured this variation, so it continues operating at $f_{VSG} = 50Hz$. According to equation 2.3, $P_3 > P_2$, meaning that even without detecting the network issue, the GFM system is already supplying additional power.

Now, consider t_4 as a slightly later moment when the VSG system has measured the output power variation. The grid is still decelerating and the VSG inverter will have begun adjusting its angle to match the grid's, following an inertial algorithm, thus slowing down to $f_{VSG} < 50Hz$. The grid will stabilize at a new frequency $f_r < 50Hz$, until secondary reserve actions are initiated. In the meantime, the VSG inverter will tend toward the same frequency, also contributing to primary regulation.

The GFM system can provide the desired inertial response, as long as it remains within the following limits.

- Capability of the DC-side energy source to maintain the DC link voltage. When the grid experiences changes in phase angle, the active power (P) delivered by the VSG system also varies. This results in an increase or decrease in the current drawn from the inverter and an exchange of energy. The DC-side energy source is responsible for supplying this energy, so it must have sufficient energy availability to supply or absorb energy as required by the grid.

- Power demand from the grid within the current limits of the GFM system to avoid triggering control mechanisms that limit the current to protect the system, causing a deviation from the desired inertial response. This limitation is the main disadvantage of GFM inverters compared to synchronous machines, which can typically withstand currents up to six times their rated value. The semiconductor devices that make up the IGBTs can handle overcurrents of 1.5 to 2 times the nominal value, but only for short durations, on the order of hundreds of milliseconds and certainly less than 1-2 seconds.

The limits depend on the resource and the initial operating conditions when the disturbance occurs. [Source: Terna]

Potential Application of Grid Forming to Different Resources

The most natural application of GFM is with electrochemical storage systems, as they inherently provide a DC-side energy source capable of sustaining instantaneous power variations, within certain limits (maximum current, available energy in the battery). In particular, the most limiting factor for batteries is the maximum current. In a scenario where the battery is exchanging a generic amount of power with the grid, the system has both upward and downward margin; if it is initially in absorption mode, the upward margin will be greater, and vice versa. It can provide stability services comparable to those of a synchronous machine. In the case where the battery is discharging at its nominal power, the system can regulate both P and Q with a margin that depends on the direction of the disturbance. If the $ROCOF < 0$, the upward margin is reduced due to the current limit. Finally, even when the system is set to exchange no power with the grid, it can remain connected in GFM mode and continue to provide regulation and stabilization to the grid if required.

Another application of grid-forming is in wind farms. In this case, the intrinsic energy of the wind turbine stored in the rotation of the blades is utilized. When connected using GFM control, this inertia can be harnessed similarly to a synchronous machine: the AC side draws more current, which is reflected on the DC side. This increases the braking torque on the wind turbine rotor, thereby providing additional power. With wind turbines operating at maximum power, it is possible to provide inertia in only one direction (in response to under-frequency events), as exceeding this limit would surpass the maximum allowable blade speed. With turbines operating at low power, there's a risk they might stall if they slow down. Therefore, it's better not to use GFM in this case. In contrast, if the wind turbine operates at an intermediate power level, it can provide both upward and downward regulation. To extend the ability to provide GFM services over longer periods, electrochemical storage systems can be added to wind farms, interfaced on the AC side. Equipped with their own inverter, these storage systems can be designed for GFM similar to a stand-alone battery (previous case). The savings come solely from sharing the costs of civil works.

Regarding the application of GFM to photovoltaic systems, under normal conditions, a photovoltaic system does not have available energy on the DC side to provide. It can only reduce its power output and offer an energy margin if subjected to planned curtailment.

Chapter 3

The Hypergrid Project: Enhancing the Infrastructure of the Italian Transmission Network

The Hypergrid project, developed by Terna, is essentially based on the creation of high-capacity direct current corridors (HVDC) running from the South to the North of Italy, designed to increase exchange capacity between different Market Zones. In the development of Hypergrid, Terna considered the following drivers.

- Synergies with existing and underutilized assets: this involves upgrading existing 380 kV and 220 kV power lines by converting them from alternating current (AC) to direct current (DC) along the same route or nearby.
- Potential reuse of decommissioned areas: these spaces can be utilized for new purposes, such as installing conversion stations required for developing new DC corridors.
- Increased network security and robustness: by strengthening the interconnections between internal Market Zones using DC technology, greater dynamic stability and reliability of the grid is obtained, as well as the system's response to possible disturbances between Northern and Southern Italy and the European grid (aiming to reduce electromechanical oscillations in the interconnected European system).
- Modular approach: this strategy facilitates the construction of infrastructure in successive steps, allowing development to proceed according to the actual location of renewable energy plants, while prioritizing the most critical corridors in terms of urgency during the implementation phase.

The new Hypergrid network is an effective, innovative, and cost-competitive solution aimed at ensuring full interoperability and synergy between the HVAC network and the various HVDC projects. It is structured into five main corridors, showed in figure 3.1:

- **HVDC Milan – Montalto**;
- **Central Link**;
- **Sardinian Corridor**, which includes the HVDC Fiumesanto – Montalto (Sapei 2) and the Sardinian Link;
- **Ionic-Tyrrhenian Corridor**, encompassing the HVDC Priolo - Rossano - Montecorvino - Latina;
- **Adriatic Corridor**, which includes the planned HVDC connections from Foggia to Forlì.

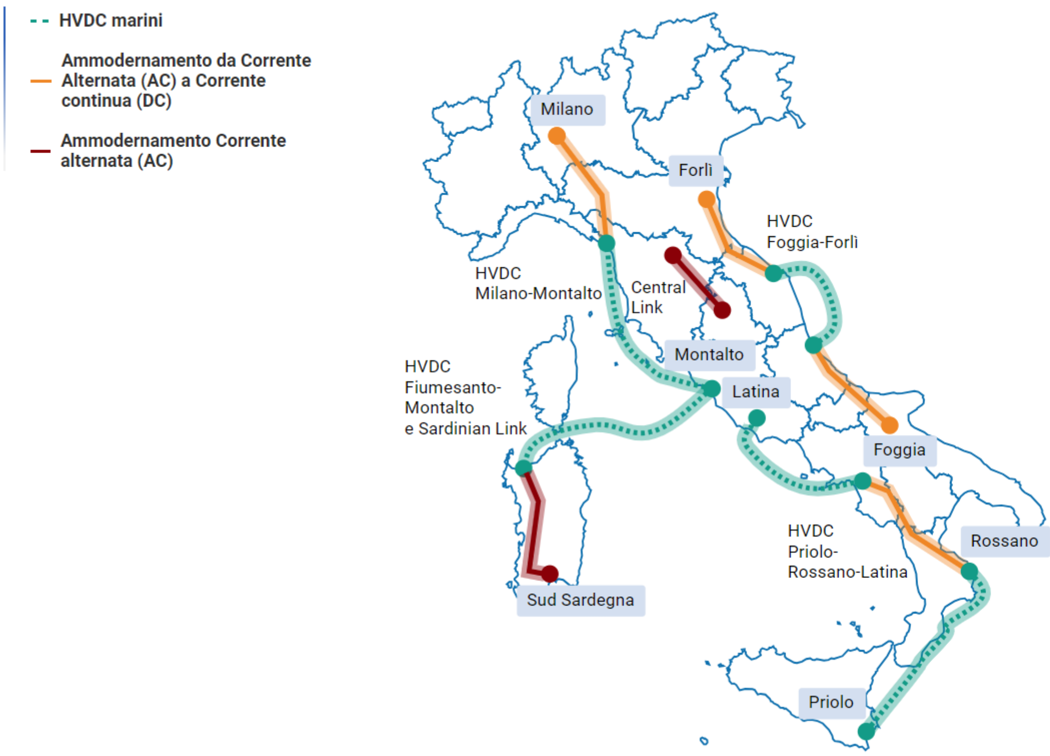
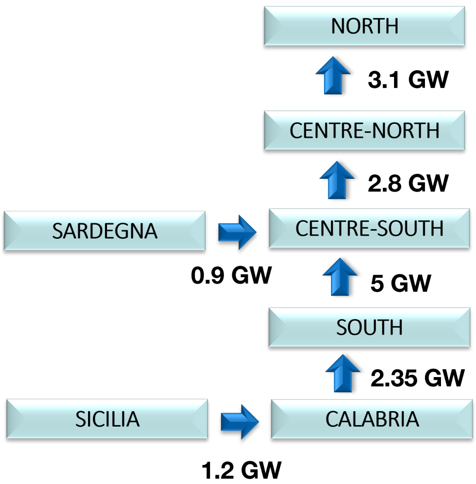
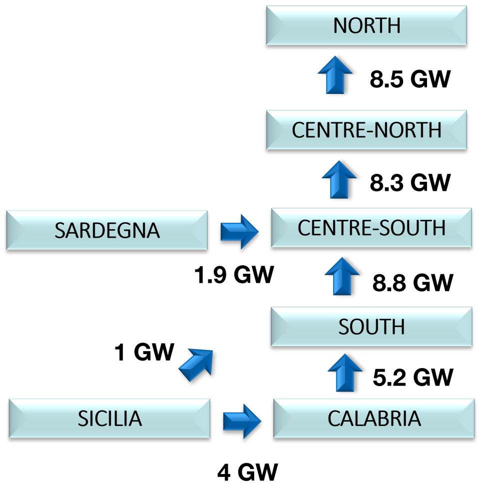


Figure 3.1: Infrastructure interventions included in the Hypergrid project. [3]

Overall, the Hypergrid project will involve the construction of approximately 13 GW of new AC/DC conversion stations, over 2500 km of DC infrastructure including overhead lines and submarine cables, and more than 400 km of AC transmission lines rebuilt with innovative new support structures named as "5F". [3] This project will double the current exchange capacity between Market Zones from about 16 GW to over 30 GW, also by leveraging capital-light solutions. Figure 3.2a shows the exchange capacity limits (winter case) between Market Zones in 2022, considering the use of Remote Disconnection (*Telescatti*) logics. Figure 3.2b shows the target limits that will be achieved with the implementation of Hypergrid and of the other infrastructural interventions contained in the Development Plan of Terna (*Piano di Sviluppo 2023*).



(a) Exchange capacity limits - 2022.



(b) Target limits - Hypergrid.

Figure 3.2: Exchange capacity limits between Market Zones in 2022 and target limits achieved with the Hypergrid project. [Source: Terna]

3.1 Capital Light Interventions

Capital light interventions are widely used by Terna as part of the Hypergrid project. These interventions are innovative solutions characterized by very short implementation times and low costs, that help make better use of existing assets. They address grid limitations and reduce issues until the interventions listed in the Development Plan of Terna (*Piano di Sviluppo 2023*) are completed. Additionally, they allow for safer and more effective management of the system during events or contingencies with high transient power surpluses.

Capital light interventions involve identifying innovative criteria that can be applied within defense systems. This includes adjusting current Remote Disconnection or Curtailment logic, also developing new approaches. The interventions also cover the installation of Dynamic Thermal Rating (DTR) systems and targeted solutions to address capacity limits of network elements that act as 'bottlenecks' and cause interference with other lines. [3]

3.2 High-Voltage Direct Current (HVDC) Technology

The Hypergrid network employs a Multi-Terminal DC configuration (MTDC) using Voltage Source Converters (VSC) and DC Circuit Breakers (DCCB). In this network, Terna utilizes voltages of 500 kV and standardized power ratings of 1000-2000 MW. [3] [12]

An HVDC network is established when more than two converter stations are interconnected via cables or overhead lines. Each HVDC converter station links the HVDC network to the HVAC network. This type of HVDC network, often called "overlay

DC grid," acts as an integrated backbone with the existing HVAC network. The various DC terminals serve multiple purposes: providing ancillary services, independent control of active and reactive power for voltage and frequency regulation, damping inter-area power oscillations, optimizing power flow close to the thermal limits of the HVAC network, and enhancing overall transmission network stability and flexibility.

In a HVDC network, conduction losses of active power are relatively low compared to HVAC transmission networks. The high and precise control of the HVDC network, in terms of active and reactive power from each HVDC station, allows for overall optimization of the parallel HVAC corridors and relies on a stable DC voltage. This stability is maintained by one or more HVDC stations acting as reference nodes for the DC network, thus managing the exchange of active power between the HVAC network and the entire HVDC network to keep the DC voltage at a set value. Maintaining a reasonable level of DC voltage is crucial for ensuring high performance in controlling active and reactive power. If converters lose this control due to low DC voltage, it can lead to a voltage collapse in the HVDC network and may also impact the parameters of the coupled HVAC network.

An important feature of VSC technology is the independent control of active and reactive power. Even with zero active power, the full range of reactive power can still be utilized. This allows the HVDC converter to function as a STATCOM, supporting grid voltage. Additionally, HVDC transmission can play a key role in frequency stability by adjusting active power based on frequency measurements. Frequency control can be designed to be either slow, contributing to secondary control, or very fast, enhancing system resilience by supporting primary frequency control (Grid Forming mode). [12]

3.3 The 5-Phase (5F) Supports

The exercise, design, and renewal of high-voltage power lines are often hindered by aspects related to the electromagnetic fields generated by them, especially in areas with high human development where new infrastructure and housing (receptors) are being built. Italian legislation concerning the maximum values of electromagnetic fields produced by high-voltage lines is very stringent and often limits the load capacity of existing lines. Specifically, the DPCM of July 8, 2008, sets a quality objective of a median value for magnetic induction over a 24-hour period equal to $10\mu T$, which decreases to $3\mu T$ in the case of new power line designs. These limits are significantly more restrictive compared to what is suggested by international technical and medical bodies (EU directive: $100\mu T$). The maximum median value of magnetic induction corresponds to a maximum current value, which is often lower than the thermal limit imposed by CEI 11-60, which defines the thermal limit ratings of overhead power lines that make up the Italian electric grid with a voltage $>$ 100 kV. A typical example is the presence of a receptor in a span of a 220 kV line, which limits its operating median from 1115 A (winter thermal limit of the conductor) to 500 A. As a result, there is a risk of line capacity limitations, impacting the decarbonization process due to the increased difficulty in transporting renewable energy.

The 5-Phase (5F) power line project was developed to create high-capacity power lines with low electromagnetic fields. As shown in figure 3.3, these supports use a geometry

Figure 3.3: Structure of a 5F electrical support. [Source: Terna]

composed of 5 conductor bundles. The spatial arrangement of the conductors, an optimal solution considering multiple mechanical and electrical constraints, allows for a significant reduction in the magnetic induction. With the same effective height and the presence of sensitive receptors, and with a lower overall height, the 5F supports enable an extremely reduced magnetic induction, comparable to that of an underground cable line. This allows power lines to operate with higher currents and, consequently, larger power capacities, potentially tripling the power compared to traditional single three-phase power lines. By using 5F supports for 220 kV power lines, it is possible to transmit 900 MW over a distance of about 250 km, while complying with thermal limit capacity and voltage drop constraints. An upgrade of the 220 kV lines in the national grid with 5F solution would enable the transmission of significantly higher power over substantial distances, which until now was only achievable with 380 kV power lines. Moreover, for 380 kV power lines, adopting 5F supports makes it possible to transmit over 3000 MW over a distance of 400 km. Such performance has so far only been achievable through more complex and costly solutions, such as higher voltage levels (e.g., 1000 kV) or HVDC power lines.

Additionally, by adopting the 5F Skyline option, which features a greater height compared to the standard 5F solution, it is possible to achieve a magnetic induction isoline with a value of $3\mu T$ at over 2.5 meters above the ground, even directly beneath the power line. For reference, the same magnetic induction value at 2.5 meters above the ground in the case of a single three-phase power line is achieved at a distance of more than 20 meters from the line's axis, and at about 17 meters from the axis in the case of a double three-phase power line. Figure 3.4 shows a comparison of the dimensions between traditional single and double three-phase power lines and the new 5F and 5F Skyline power lines.

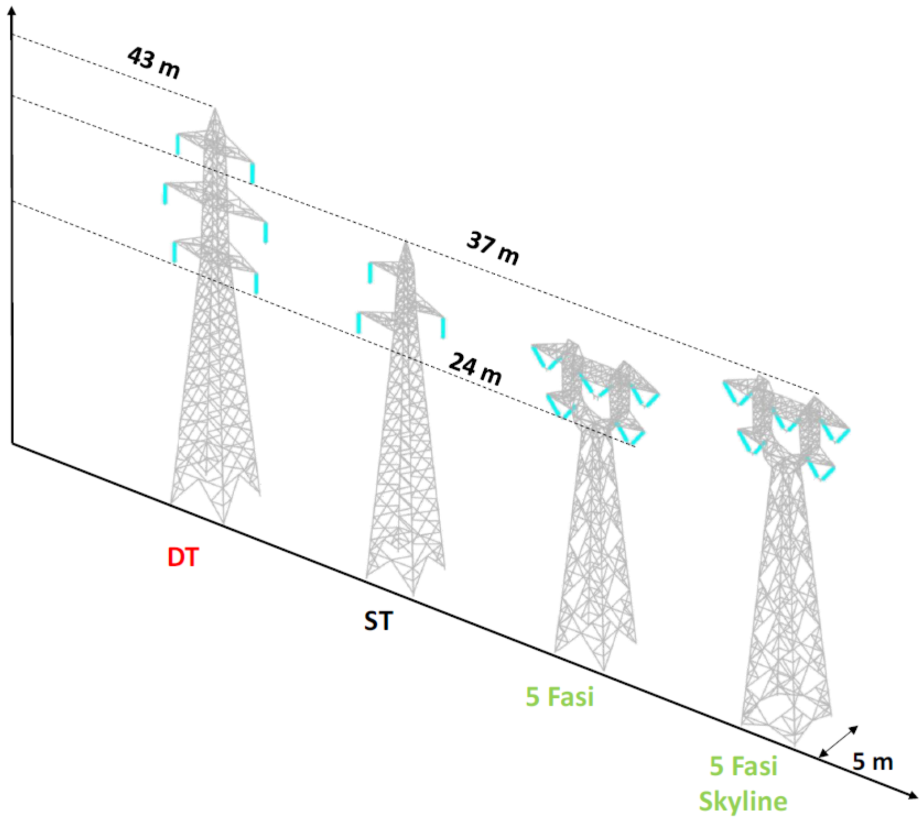


Figure 3.4: Comparison between traditional supports, 5F and 5F Skyline supports. [Source: Terna]

The new 5F supports have been designed to ensure low levels of noise and radio interference, which are lower than those of conventional power lines and compatible with operation in highly populated areas. Moreover, according to a study by Terna, the 5F supports have less visual impact compared to single three-phase towers, due to their reduced height and the transparency of the tower structure. As for the 5F Skyline towers, the visual impact is comparable to that of a single three-phase tower.

Last but non least, another positive feature of the 5F supports is that they allow for the maximum utilization of existing assets: thanks to the use of transition supports, the 5F technology enables the renewal of individual sections of power lines, specifically in areas with sensitive receptors such as residential buildings. [Source: Terna]

Chapter 4

Forecasting the Evolution of Italy's Transmission Grid: Insights from Terna's Simulation Analysis

The trend of increasing renewable energy sources (RES) throughout the last years, alongside newly authorized grid connections and long-term targets, highlights the need for careful monitoring of both new plants to be connected to the Italian Transmission Network and grid modifications. This is crucial for Terna in order to identifying and preventing potential issues through timely and coherent solutions.

The following analysis focuses on local congestion and is part of a study for the target year 2025. The 2025 model is developed based on the 2023 grid, in particular starting from a snapshot characterized by high renewable penetration and low demand. The connections planned for 2024 and 2025 have been modeled according to the forecasts for authorized HV RES plants expected by the end of 2025. Specifically, two national scenarios have been constructed, Medium and Maximum Pumping Scenario, with different values of pumping in the Central-South, Sicily, and Sardegna, as well as two focused scenarios with increased RES productivity in regions with the highest wind and solar impact, Lazio and Campania respectively. Using the WinCreso software for the simulations a static analysis under N and N-1 conditions have been conducted.

This analysis will provide a basis for understanding potential grid congestion and the necessary interventions as part of the long-term integration of RES.

4.1 Initial Snapshot: Baseline Conditions for the Simulations

The study aims to highlight grid congestion in the presence of large amounts of renewable energy sources. To identify this type of issue, we chose to start from a snapshot that actually occurred in April 2023. The selected day was April 14, 2023, at 1:00 PM, because at that moment, the production from renewable sources, particularly wind power, was very high. Additionally, since it was the middle of the daylight hours, solar power was also generating significantly. The energy production breakdown by source at the moment the snapshot was taken can be seen in figure 4.1.

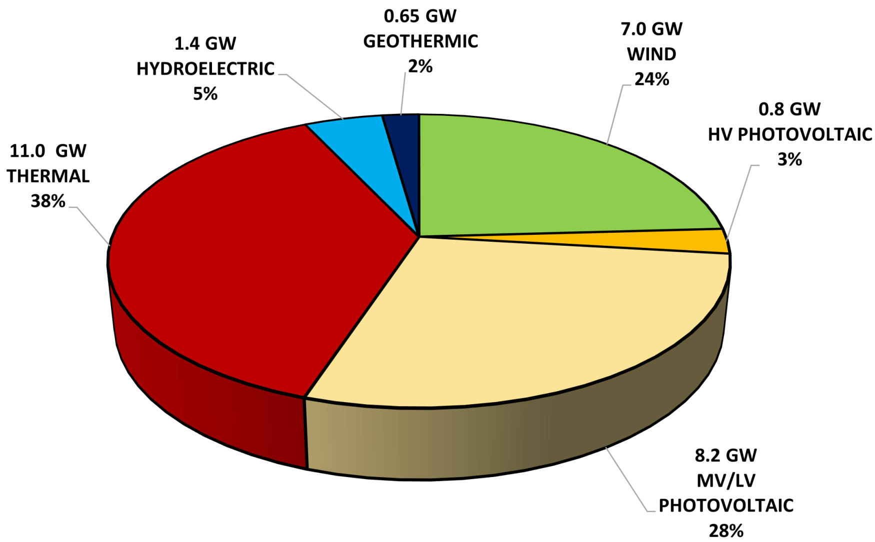


Figure 4.1: Energy production breakdown by source at 1:00 PM on April 14, 2023. [Source: Terna]

4.1.1 Calculation of the Producibility Indexes

The producibility indexes were calculated using Terna's data on hourly production balance, extracting specific hourly photovoltaic and wind production values over the 2021–2023 period. Starting from these data, the producibility indexes ($P_{\%}$) for high-voltage photovoltaic and wind power were calculated using the following formula:

$$P_{\%} = \frac{P_{produced}}{P_{rated}} \cdot 100 \tag{4.1}$$

where $P_{produced}$ is the actual RES production in the considered period and P_{rated} is the installed rated power of all RES plants.

The producibility indexes chosen for wind and photovoltaic in the simulations correspond to the 97^{th} percentile of annual hours. This selection represents conditions of high production for RES plants, excluding a limited number of hours, 3% of the year, in which higher values were recorded.

The calculation of the producibility indexes was performed at the national level: a single index was found for photovoltaic and a single index for wind power, corresponding to 50% and 60%, respectively. However, it was observed that in certain geographic areas, these national indexes are significantly lower than the actual values. These regions are Lazio for high photovoltaic production, and Campania for high wind power production. For this reason, and to simulate in a more realistic way the significant impact of the new FER plants, for Lazio and Campania specific simulations were developed using the realistic values, while the national values have been applied to the two national scenarios. In table 4.1 the different producibility indexes for these regions are shown. For what concerns the photovoltaic installed on medium and low voltage networks, which will be referred to as distributed generation, the national calculated producibility index is 35%.

PRODUCIBILITY INDEXES for HV RES			
	National value	**Lazio**	**Campania**
Wind	**60%**	National value	80%
Photovoltaic	**50%**	70%	National value

Table 4.1: Producibility indexes for Italy and specific regions. [Source: Terna]

The producibility index is highly relevant in the modeling of the electrical system for the purposes of this study. It quantifies the efficiency of the plants by indicating the instantaneous production as a percentage of their maximum installed nominal capacity. It is important to specify that the producibility indexes used for these simulations should not be considered valid for all other moments of the year or day. In fact, producibility indexes vary due to numerous factors, including inefficiencies in the energy conversion processes, limited availability of non-programmable sources, downtime due to maintenance or failures, or grid constraints that may lead to production curtailment.

4.2 Grid Modeling and Updated RES Capacities

Starting from the situation described on April 14, 2023, with high renewable production, the operation of the Italian transmission grid has been simulated under the same conditions but with increased installed RES capacity, and consequently higher RES power production, to match the levels expected by the end of the target year 2025.

The simulation software used for the static analysis is WinCreso, employed by Terna for transmission grid security analyses in N and N-1 conditions. To perform the simulations, it is necessary to import the "Dadir" network data into WinCreso, which are commonly referred to as "*rete muta*" in Italian. These data contain the grid topology and parameters related to all network elements. Therefore, the "Dadir" data corresponding to the snapshot of the 2023 grid were modified to simulate the grid at the end of 2025. To modify the "Dadir" data, another software called Teseo, which is still in the experimental phase, was utilized. The modifications made to the "Dadir" data are essentially of two types: the new RES plants and the interventions aimed at developing the Italian transmission grid.

For what concern the new RES plants connected at high voltage, only those already authorized, or in advanced stages of authorization by Terna, scheduled to be operational by 2025, were modeled. In fact, considering all connection requests, even those at less advanced stages of the authorization process, would have been unrealistic, as it is unlikely that the bureaucratic procedures could be completed by the end of 2025.

Following the modeling of the new RES plants, an installed photovoltaic capacity of 36.9 GW was obtained, with 32% of this capacity located in Sicily, 31% in Lazio, and 14% in Sardinia. For wind power, a total installed capacity of 14.5 GW was achieved, with 28% of this capacity in Puglia, 19% in Campania, 17% in Sicily, and 14% in Basilicata. In table 4.2 the increment of the RES installed capacities with respect to the year 2023 are shown. The values in this table should be interpreted considering that the majority of wind installed capacity is connected to high voltage, while only 9% of solar power's total installed capacity is currently connected to HV, with most connections made at medium and low voltage levels.

HV WIND and PHOTOVOLTAIC				
	Installed 2023	**Increment**	**% Increment**	**Installed 2025**
Wind	12.3 GW	2.2 GW	18%	14.5 GW
Photovoltaic	30.2 GW	6.7 GW	22%	36.9 GW

Table 4.2: Increment of RES plants from 2023 to the end of 2025. [Source: Terna]

In the production balance of the snapshot taken on April 14, 2023, at 1:00 PM, as shown in figure 4.1, a significant portion is represented by the distributed generation of photovoltaic. It is important to note that distributed generation was not modeled in the "Dadir" data, which refer to the high-voltage transmission grid, but was instead considered as a load reduction at primary substations, where the high-voltage transmission grid connects to the medium-voltage distribution network. In the simulations for 2025 the load reduction correspond to a distributed generation installed capacity incremented by 4.8 GW with respect to 2023.

Regarding the developments in the grid, reference was made to the scheduled interventions for 2025 outlined in the *Piano di Sviluppo 2023* [3], and to more recent updates from Terna on the actual progress of the projects.

4.3 Developing National Scenarios: Minimum and Maximum Pumping Conditions

To carry out the simulations, two national scenarios were created: one with medium pumping values, Medium Pumping Scenario, and one with maximum pumping values, Maximum Pumping Scenario. This was done to highlight how the planned use of pumping technology can alleviate grid issues during hours of high RES production. The same concept can be applied to storage systems, mainly BESS (Battery Energy Storage Systems), as their installations on the high-voltage grid will increase in the coming years. In the current section, both scenarios, along with the focus scenario for the Lazio region, will be described in detail.

It should be noted that in the initial 2023 snapshot situation, some RES plants were in operation while others were out of service. In simulating the 2025 scenarios, the plants that were out of service were not activated, while those that were operational were assigned the same power output they had in the initial 2023 snapshot. All new photovoltaic and wind RES plants were activated, with their installed capacity multiplied by the producibility indexes calculated from the initial snapshot data, to ensure production values consistent with those of the existing plants in the starting snapshot. Consequently, by applying a producibility index of 50% to the 6.7 GW of newly installed high-voltage photovoltaic capacity, a production of 3.35 GW was obtained, and by applying a producibility index of 60% to the 2.2 GW of newly installed wind capacity, a production of 1.32 GW was achieved.

Considering the distributed generation, multiplying the 4.8 GW of newly installed capacity by the producibility index of 35% yields a production value of 1.68 GW.

Thermal production was reduced to the minimum level required to maintain network adequacy and security requirements. Additionally, imports from abroad were reduced, mainly in the North, while exports from the South, Central-South, and Sicily were maximized, directed respectively to Malta, Montenegro, and Greece.

The energy production breakdown by source in the national scenario simulations can be seen in figure 4.2.

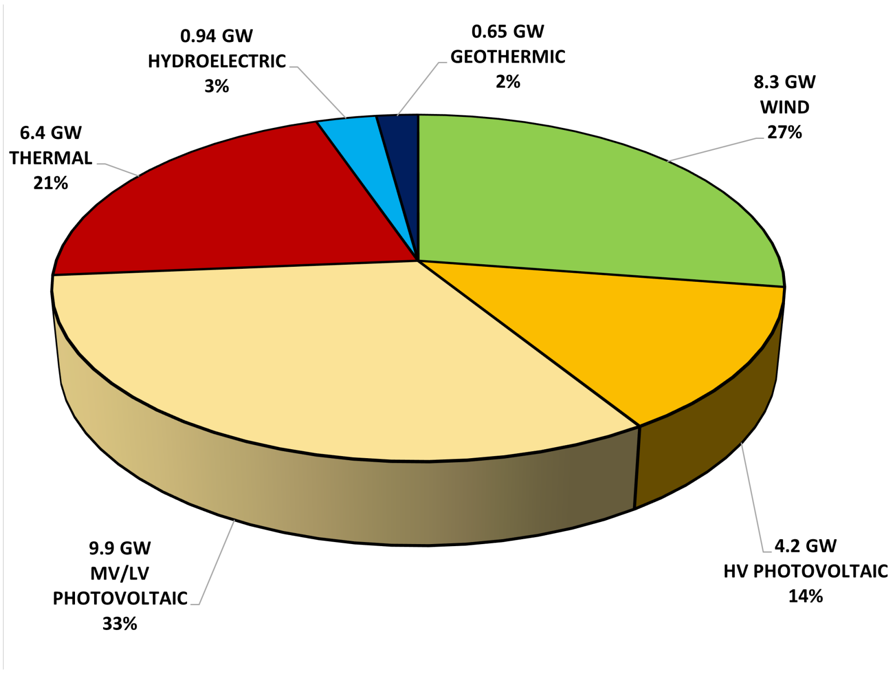


Figure 4.2: Energy production breakdown by source in the national simulations for 2025. [Source: Terna]

The two national scenarios, Medium Pumping Scenario and Maximum Pumping Scenario, were developed starting from the production values shown in figure 4.2. In table 4.3 the pumping values for the two national scenarios are presented, divided by Market Zone.

NATIONAL SCENARIOS: PUMPING VALUES		
Market Zone	**Medium Pumping Scenario**	**Maximum Pumping Scenario**
Center-South	500 MW	1000 MW
Sicilia	150 MW	650 MW
Sardegna	160 MW	160 MW
Total	**1810 MW**	**810 MW**

Table 4.3: Pumping values set for the two national scenarios. [Source: Terna]

The focus scenario for the Lazio region was developed based on the Maximum Pumping Scenario, applying a producibility index of 70% to the photovoltaic plants in the region. This scenario was necessary to simulate, with more realistic producibility values, the significant production expected in this area, following a substantial increase in installed photovoltaic capacity projected for 2025.

4.4 N-1 Security Analysis for National Scenarios: Results and Violations

This section reports the violations in N-1 conditions identified in the Medium Pumping Scenario, Maximum Pumping Scenario and in the Lazio focus scenario, along with the solutions proposed by Terna. No violations were observed in intact network conditions (N conditions) across these three scenarios.

In tables 4.4, 4.5 and 4.6, the elements of the network in violation are presented by zone, along with their voltage level and the percentage of overload they have reached. For this analysis, all lines with overloads greater than 120% were considered. This value was chosen because Terna defines a transient operating current limit of 120% of the corresponding continuous operating current limit. This higher current can flow for up to 20 minutes, provided that in the previous 30 minutes it stayed below 80% of the continuous limit. During these 20 minutes, network maneuvers can be implemented to mitigate the overload. Additionally, autotransformers (ATs) are assumed to withstand overloads up to 108% of their nominal power and current, as specified by manufacturers.

In Central Italy, there were 13 lines with violations, all operating at 150 kV. This number is notable when compared to the total of 1,518 Terna lines in the region, of which 1,363 operate at 150 kV or below. Additionally, three 380/150 kV ATs experienced violations, distributed across two substations.

Concerning South Italy, there were 8 lines with violations, 7 operating at 150 kV and 1 at 220 kV. In this area the total lines of Terna amounted to 816, of which 81 operate at 220 kV and 667 operate at ≤150 kV. Moreover, two 380/150 kV ATs experienced overloads, both located at the same substation.

In Sardinia, there are 190 lines in total, 154 of which operate at 150 kV or below, and only one of these experienced an overload. Finally, in Sicily, there were 10 recorded violations, with 6 lines at 150 kV and 4 at 220 kV. This is out of a total of 369 lines, of which 40 operate at 220 kV and 315 at 150 kV or below. The overloaded 380/220 kV ATs in Sicily were two, both located at the same station.

N-1 VIOLATIONS: CENTRAL ITALY		
Violated Element	**Nominal voltage [kV]**	**I% MAX**
Line 1	150	168%
Line 2	150	135%
Line 3	150	132%
Line 4	150	134%
Line 5	150	193%
Line 6	150	153%
Line 7	150	133%
Line 8	150	137%
Line 9	150	141%
Line 10	150	122%
Line 11	150	128%
Line 12	150	135%
Line 13	150	125%
AT1 380/150 kV (Node A)	400 (primary)	122%
AT2 380/150 kV (Node A)	400 (primary)	122%
AT1 380/150 kV (Node B)	400 (primary)	158%

Table 4.4: Violations in N-1 conditions identified in the Medium Pumping Scenario, Maximum Pumping Scenario and in the Lazio focus scenario for Center Italy. [Source: Terna]

N-1 VIOLATIONS: SICILY AND SARDINIA		
Violated Element	**Nominal voltage [kV]**	**I% MAX**
Line 1 - Sardinia	150	144%
Line 1 - Sicily	150	124%
Line 2 - Sicily	150	138%
Line 3 - Sicily	150	126%
Line 4 - Sicily	150	123%
Line 5 - Sicily	150	136%
Line 6 - Sicily	150	135%
Line 7 - Sicily	220	130%
Line 8 - Sicily	220	129%
Line 9 - Sicily	220	124%
Line 10 - Sicily	220	123%
AT1 380/220 kV (Node A) Sicily	400 (primary)	122%
AT2 380/220 kV (Node A) Sicily	400 (primary)	105%

Table 4.5: Violations in N-1 conditions identified in the Medium Pumping Scenario, Maximum Pumping Scenario and in the Lazio focus scenario for Sicily and Sardegna. [Source: Terna]

N-1 VIOLATIONS: SOUTH ITALY		
Violated Element	**Nominal voltage [kV]**	**I% MAX**
Line 1	150	158%
Line 2	150	153%
Line 3	150	138%
Line 4	150	122%
Line 5	150	135%
Line 6	150	120%
Line 7	150	122%
Line 8	220	124%
AT1 380/150 kV (Node A)	400 (primary)	109%
AT2 380/150 kV (Node A)	400 (primary)	109%

Table 4.6: Violations in N-1 conditions identified in the Medium Pumping Scenario, Maximum Pumping Scenario and in the Lazio focus scenario for South Italy. [Source: Terna]

For each of these violations identified through the static analysis of the scenarios, Terna has determined the necessary mitigation and congestion resolution actions. The identified interventions can be grouped into three summary categories.

- Maximization of existing assets: increasing the network elements maximum current thresholds through reconductoring interventions and replacement of equipment, such as autotransformers (ATs).
- Anticipation of planned structural interventions: new substations and associated connections, new lines, establishment of permanent connections for new RES plants, and new transformers.
- Installation of Dynamic Thermal Ratings (DTR) to dynamically and in real-time calculate the maximum ratings of the lines.

These interventions will resolve network congestion without requiring the curtailment of wind or photovoltaic production.The reduction of thermal production cannot be a solution, as during hours of high renewable production, it is already minimized to the necessary level to ensure grid stability.

4.4.1 Transit Limit Analysis between Market Zones

For the Medium Pumping Scenario and the Maximum Pumping Scenario, compliance with the transfer limits between Italian Market Zones was also analyzed.

In the Medium Pumping Scenario, transfers exceeding the limits are highlighted from the Center-South to the Center-North and from Sicily to Calabria. The interzonal limit is not respected, whether considering the current value or the projected value for the end of 2025 after the planned reinforcement activities. In the Maximum Pumping Scenario, the only limit that is not respected is the transfer from the Center-South to the Center-North. However, this issue does not arise when considering the projected 2025 limits values.

Table 4.7 presents the transfer values between Market Zones resulting from simulations of the Medium Pumping Scenario and Maximum Pumping Scenario, alongside the current interzonal limits and those projected for the end of 2025.

TRANSFER VALUES BETWEEN MARKET ZONES				
	Medium Pumping Scenario transfer [MW]	**Maximum Pumping Scenario transfer [MW]**	**Interzonal limit 2024 [MW]**	**Interzonal limit 2025 [MW]**
Center-North → North	2857	2202	3100	-
Center-South → Center-North	3914	3274	2800	3500
South → Center-South	5072	4650	5100	-
Calabria → South	1983	1619	2350	-
Sicily → Calabria	1786	1245	1300	1650

Table 4.7: Transfers between Italian Market Zones and compliance with interzonal limits. [Source: Terna]

4.5 Campania Scenario Case Study: Addressing Violations and Implementing Solutions

The focus scenario for the Campania region has been built on the Maximum Pumping Scenario, applying a producibility index of 80% specifically to the region's wind power plants. This value of producibility index is the highest value reached in the region in 2023. By applying an 80% of producibility index to the region's wind power plants, an additional 200 MW of wind production was achieved. This scenario enables a more accurate simulation of the substantial production expected in Campania, driven by the significant increase in installed wind capacity projected for 2025. Currently, this area already records high levels of curtailment of wind production resulting in high values of missed wind production (*MPE - Mancata produzione eolica*).

Figure 4.3 illustrates the network layout and operational setup at the nodes where the simulations in this scenario have highlighted critical issues. A rapid remote disconnection of generation system (*Telescatto*) is in service to ensure safe parallel operation of the two autotransformers (AT) 380/150 kV at node A. If one of the two ATs trips, the wind production in the area will be disconnected until it reaches a level that does not exceed the nominal capacity of one of the two ATs, with up to 130 MW of power potentially curtailed. This technique is increasingly being used to resolve congestion issues in N-1 conditions, as it represents a smart solution for managing network operation problems by utilizing defense systems. To manage situations with high wind production, as in the simulations, the 150 kV network configuration used in this area involves the formation of four radial connections. The first connection involves nodes B and C. The second radial connection concerns node D, and is achieved by opening the circuit breaker on the line that links it to node F. The third connection is established by disconnecting the two busbars in node E: this allows part of the production present in node E to be directed to one busbar that connects to node A, while another portion of the production stays on the other busbar, which connects to node G. This second busbar in node E together with node G represent the fourth radial connection.

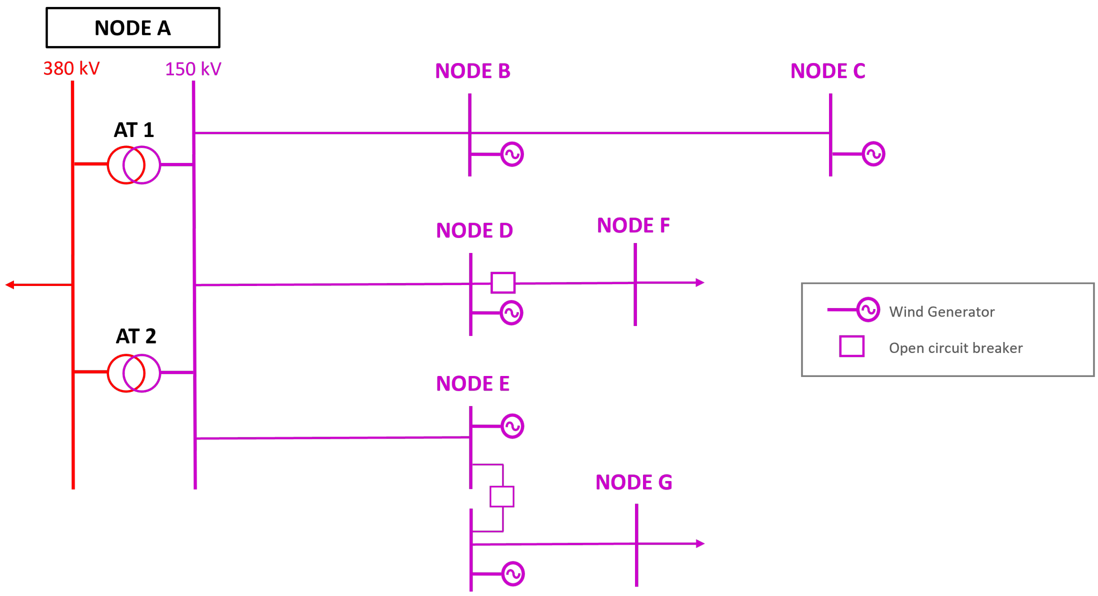


Figure 4.3: Network layout and operational setup. [Source: Terna]

The simulation results were compared with both the winter and summer current limits and has been considered that the ATs can be loaded up to 108% of their nominal power. In this configuration, violations are observed even in N-state simulation, unlike previous configurations where violations only appeared in N-1 analysis.

As shown in Figure 4.4, with the current network configuration, the wind production simulations result in overloading both ATs at node A at 120%, as well as two lines, despite these lines already being equipped with Dynamic Thermal Rating (DTR) systems.

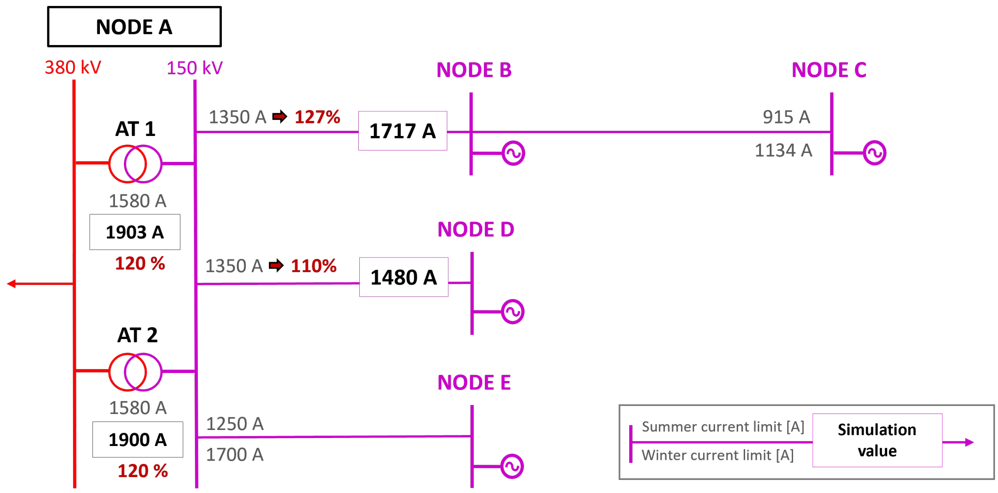


Figure 4.4: Simulation results with the current grid. [Source: Terna]

A partial solution has been identified in replacing the conductors of lines A-B and A-D to increase their target capacity to 1500 A for summer and 1600 A for winter, as shown in figure 4.5. This adjustment fully resolves the overload on line A-D, while for line A-B, the overload is reduced to 107% in winter and 114% in summer. Overloads remain on the two ATs.

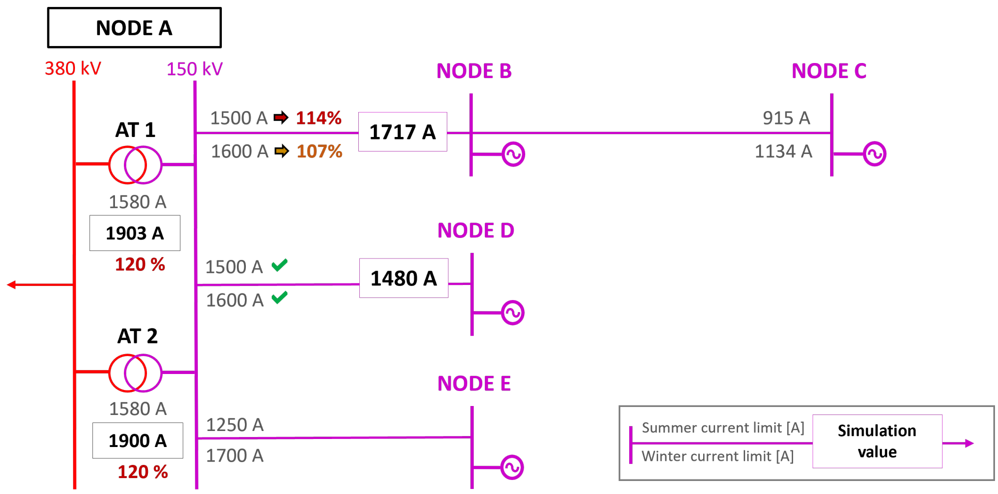


Figure 4.5: Simulation results after the substitution of lines A-B and A-D. [Source: Terna]

The next solution identified to ensure safe network operation was to increase transformation capacity, with the network configuration for this setup shown in figure 4.6. By installing a third 250 MVA AT, all the ATs will be able to operate without risk of overload at all times. The addition of a third AT would reduce winter overloads on lines A-B, B-C and A-D to very low levels, about 103% and 104%, nearly eliminating the need to curtail wind production. However, in the summer configuration, this setup would still result in overloads on these lines. In particular, the overload values obtained for line A-D would be very low (103%), while lines A-B and B-C would experience levels of 110% and 129%. However, these violations are based on static line capacity limits, highlighting the opportunity to install DTR systems on lines A-B and B-C to enable the use of dynamic capacity limits during summer operation.

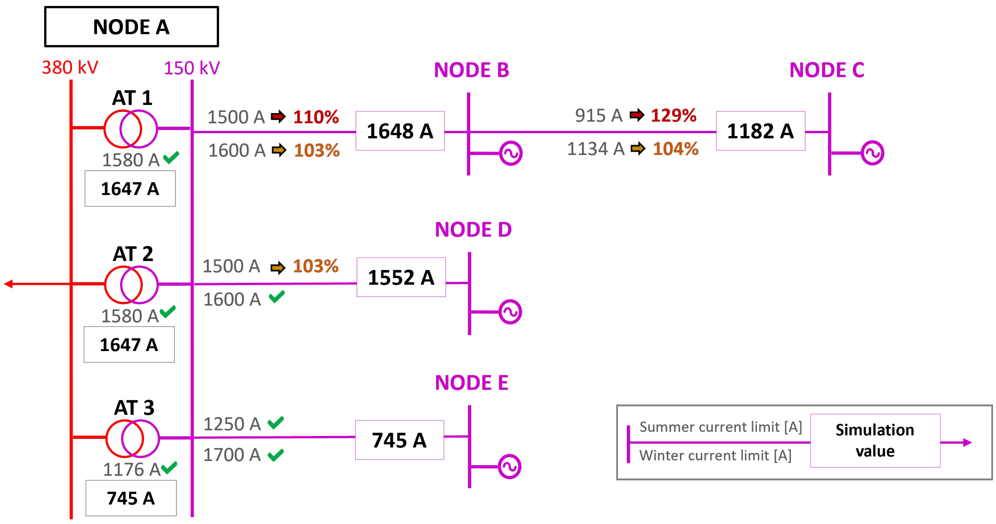


Figure 4.6: Simulation results after the substitution of lines A-B and A-D and the installation of the third AT. [Source: Terna]

The necessary interventions identified by this analysis, including the upgrading of lines A-B and A-D and the installation of a third autotransformer at node A, will not be the only upgrades planned for this area: a new substation is also scheduled for construction in 2027. These initiatives will work in synergy to enhance the operational reliability and security of this section of the central-southern transmission network.

Chapter 5

Conclusions

This dissertation analyzed the Italian Transmission Network, identifying challenges in integrating new RES capacities in high-production areas. Modeling various scenarios and future RES installations led to identifying technical solutions to improve network reliability and security.

Among the proposed solutions, adopting Dynamic Thermal Rating (DTR) and reinforcing existing lines effectively optimizes transmission capacity during high RES production. Another smart solution is rapid remote disconnection, an increasingly adopted technique for resolving congestion issues in N-1 conditions. This approach manages network operation issues by using defense systems. With the projected RES development, new substations and transmission lines are expected, strengthening the infrastructure in synergy with other enhancement measures.

Despite the significance of the results, some limitations should be noted. A primary limitation is the use of uniform producibility indexes nationwide, except for the two focus scenarios, which doesn't fully capture local variability. Future analyses could improve accuracy by using producibility indexes tailored to each geographic area. This study is also based on a specific snapshot chosen under high RES production to highlight network constraints. This approach means that the simulations capture only one possible production scenario. Real-world scenarios may vary considerably: simultaneous higher wind and solar producibility could occur nationwide or be limited to certain regions.

Future studies could focus on the impact of emerging technologies, such as large-scale storage systems, to assess their effectiveness in alleviating network congestion. Equally important will be analyzing the effect of large data centers in Northern Italy as significant new loads, potentially intensifying power flows from the South, where most renewable generation is located, to the North, where major consumption centers are situated.

In conclusion, the interventions identified in this dissertation and the outlook for network evolution represent an initial step towards a more robust electric system, prepared to support the energy transition.

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