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On the Impact of Renewable Generation on the Sicilian Power System in Near-Future Scenarios: A Case Study

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Abstract: This paper was conceived to investigate some central issues related to the upheaval of current energy scenarios in Sicily. New power connection lines that are about to be built in the Mediterranean area, planned with a view to a constantly increasing renewable generation, encourage the carrying out of analyses on how the Sicilian electric power system will be able to make itself ready to support large power injections, especially due to new renewables plants that will be established in the region soon. This study, carried out in close collaboration with the Italian TSO Terna S.p.A and the University of Palermo, defines what the impacts of new renewable power plants will be on the Sicilian power transmission grid under intact and non-intact grid conditions. This study consists of steady-state simulations carried out using WinCreso® software version 7.62.1-3 in two energy scenarios estimated for the years 2024 and 2027, based on real connection requests by producers to Terna, and allows one to go beyond the studies conducted so far on a 2030 basis through the precise identification of network nodes or lines in difficulty. Finally, as well as presenting an interesting case study due to Sicily's strategic position in the Mediterranean Sea, this article proposes a methodological approach that can easily be adopted in other contexts and by other TSOs to analyze similar situations.

Keywords: renewable energy source (RES) integration; steady-state simulations; HVDC; Sicilian power system; Mediterranean energy hub

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1. Introduction

The past decade has seen an upheaval of existing grid assets due to the increasing penetration of energy from renewable energy sources (RESs) [1]. The energy transition results in ambitious challenges in transmission grid development, starting with the goals of grid efficiency, resilience, and the security of supply and service. A profound change is taking place, characterized by a reversal of the traditional paradigm that sees the grid as a unidirectional flow of power: the management philosophy is now characterized by bidirectional power flows and the integration of sources that are highly random in terms of producible power. Contextually, the frequency and intensity of extreme weather events as a consequence of ongoing climate change necessitate the need for a new approach to electricity system management [2]. For these reasons, grid infrastructure management requires different and more refined logic compared to before. It is, therefore, essential to constantly and promptly monitor its status through accurate simulations considering the N-1 security criterion [3]. In this context, due to its pivotal role as an energy bridge between Africa and Europe [4], the Sicilian power system has been considered by the Italian TSO, Terna S.p.A., as a test bench to study operating scenarios and new technologies aimed at better management and exploitation of the high-voltage (HV) transmission system. The strategic location of Sicily indicates how the latter is a candidate to become a key energy hub at the center of the Mediterranean Sea. At the same time, the Sicilian electricity system has been under severe stress for several years due to the aging of some transmission lines and an increase in production from photovoltaic and wind power sources beyond expectations. Six of the nine Sicilian provinces have been declared high-critical areas, two medium-critical areas (Catania and Palermo), and one low-critical area (Messina), with different levels of risk, where the energy produced by the plants connected to the transmission grid cannot be distributed to the nearest loads because it is in excess of that already produced by distributed generation. The future reinforcement of the 220 kV connection with Malta and the new connections that are about to be built in the Mediterranean area, planned to steadily increase renewable generation, encourage analyses of how the Sicilian power system can make itself ready to support the large injections of power that will affect the region in the future [5,6]. Figure 1a shows Sicily's high- and extra-high-voltage transmission grid, updated to 2024, while Figure 1b shows the new configuration of the transmission grid in 2030, with the existing 220 kV connection with Malta and the two HVDC links between Sicily, Campania, and Sardinia (the so-called Tyrrhenian Link, East and West branches) and between Sicily and Tunisia (the so-called TUN-ITA Link) that will be built by Terna in the next few years, increasing power flows to and from Sicily by approximately 2500 MW. The red, green, and purple lines indicate 380 kV power lines, 220 kV power lines, and HVDC connections, respectively.

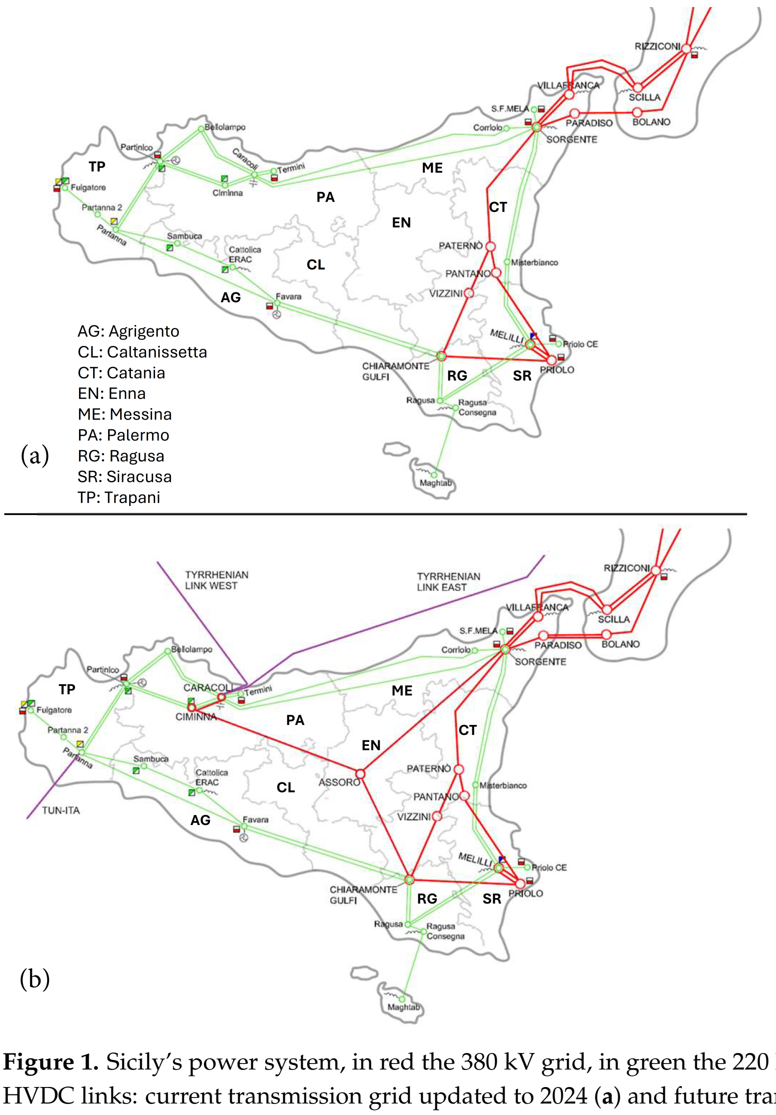

Figure 1. Sicily's power system, in red the 380 kV grid, in green the 220 kV grid and in purple the HVDC links: current transmission grid updated to 2024 (**a**) and future transmission grid updated to 2030 considering the 2023 Terna Development Plan, with the TUN-ITA Link and Tyrrhenian Link HVDC connections (**b**).

Sicily's current electricity demand is 17.5 TWh/year, which is estimated to grow by 20% by 2030. At the same time, total production is expected to increase from the current 19.9 TWh/year to 27 TWh/year (+35.7%) by the same year [7]. Because of these significant changes in power balance and power flows due to both new connections with other regions and the strong demand for new power plants from private producers, and considering the difficulties in the construction of new internal power lines, Terna has tried to optimize the use of the existing transmission lines to increase the current carrying capacity, including through the use of Low-Sag High-Temp (LSHT) heat-resistant conductors and the application of Dynamic Thermal Rating (DTR) systems [8]. Some case studies of these technologies applied to the Sicilian power system are reported in [9,10]. Many studies have already been carried out on Sicily considering future energy scenarios and new connections currently planned. The study in [11] analyzes the frequency dynamics in the case of the simultaneous opening of both the Tyrrhenian Link East and West branches under both import and export power conditions. The study in [12] presents a static analysis (power flow) under extreme load conditions and dynamic simulations with a focus on damping and oscillations in 2030 and 2040 scenarios. Refs. [13,14] examine the performance of Voltage Source Converter (VSC)-based HVDC systems with grid-forming capabilities applied to the Sicilian HVDC stations, considering the power step response, angle stability response, DC-link voltage stability, and focusing on the contribution that such installations can provide to the security of the Sicilian system. Some studies have focused on the AC interconnection line with Malta. In [15,16], the fundamental contribution of RES production to both covering Sicilian electric demand and exporting power via the new connecting cable is shown through power flow simulations in the NEPLAN 360® environment, version V9.10.5.1. Other studies have focused on different critical situations in the Sicilian grid and possible countermeasures to mitigate frequency and voltage instabilities, such as loss of thermal generation during scheduled maintenance periods when Sicily operates an electric island [17], dynamic simulation with and without synthetic inertia, primary regulation for large disturbances with different supporting services, modal analysis for small disturbances, and voltage stability [18,19]. Finally, the study in [20] reports several network analyses and provides technical and economic elements regarding the potential conversion of a Sicilian HVAC transmission line into HVDC in a 2030 scenario. Unlike the previously mentioned papers that refer to medium- or long-term scenarios (2030 or 2040), the present work aims to investigate the behavior of the Sicilian power system in short-term scenarios, specifically for the years 2025 and 2027. Consequently, all simulations, carried out using WinCreso® software version 7.62.1-3, were performed in the current grid model, made available by Terna S.p.A. This article aims to show how producers' demands for new renewable energy plants on the island can lead to congestion even in short-term scenarios, making it more urgent to plan appropriate countermeasures to keep the grid reliable, efficient, and secure. This paper is presented as a relevant case study because of Sicily's key role as a future bridge between European and African power transmission networks, but, at the same time, proposes a methodological approach that can easily be adopted in other contexts and by other TSOs to analyze similar situations in short-term scenarios. The rest of this paper is organized as follows: Section 2 describes the evolution of the Sicilian power grid up to 2030. Section 3 describes the methodology adopted for the analysis and determination of the 2024 and 2027 scenarios. Section 4 describes the output and results of the simulations. Section 5 presents a brief discussion of the obtained results, while Section 6 sets out the conclusions of this study.

2. Evolution of the Sicilian Generation and Transmission System

The uneven distribution of the production fleet and load, along with the concentration of the current 380 kV network only in the southeastern area (Figure 1), are the main peculiarities of the Sicilian region today. In the case of accidental or planned service outages on the 220 kV primary transmission grid (green line in Figure 1b), the 150 kV sub-transmission grid becomes particularly overloaded, and sometimes, generation rescheduling of the region is required. This can cause significant issues, especially in the central part of the island where the 380 kV network is absent and the 220 kV network is limited, with transmission strongly depending on the 150 kV system.

In addition, particularly complex is the management of the eastern area of the island, in particular, close to the main cities of Messina, Catania, and Syracuse. A service outage on the 220 kV "Melilli–Misterbianco" double circuit transmission line results in a redistribution of the load onto nearby 150 kV sub-transmission lines, and this, together with the imminent entry into service of new-generation renewable generation plants in the same area, is likely to saturate some portions of the sub-transmission grid, resulting in congestion risks [21]. As a response to these issues and to prevent new ones, Terna's Development Plan 2023 [22] has introduced a series of interventions planned for the Sicilian transmission grid to improve its operational security (Table 1).

Table 1. Main grid development projects planned in Sicily by Terna up to 2030.

Project	Expected Operation
New 380 kV "Bolano–Annunziata" power line	2026
New 380 kV "Chiaramonte Gulfi–Ciminna" power line	2026
New HVDC "Tyrrhenian East Link" connection	2027
New HVDC "Tyrrhenian West Link" connection	2027
New "Caracoli" AC/DC conversion station	2027
New Tunisia–Italy "TUN-ITA" interconnection	2028
New "Assoro" electrical station	2030
New 380 kV "Assoro-Sorgente 2–Villafranca" power line	2030
New 380 kV "Caracoli–Ciminna" power line	2030

The proposed configuration of the Sicilian power grid in 2030 was shown in Figure 1b. The new 380 kV "Assor–Sorgente 2–Villafranca" power line, planned for 2030, will connect the provinces of Messina and Enna, supporting the 380 kV "Sorgente–Paternò" line. The new 380 kV "Chiaramonte Gulfi–Ciminna" line will allow increased transmission capacity between the eastern and western sides of Sicily, ensuring greater RES development while reducing congestion on the 150 kV lines due to the unavailability of parts of the 220 kV coastal ring. In the context of HVDC links, the Tyrrhenian Link stands out with its 1000 MW transmission capacity, which will allow a greater exchange capacity with the mainland and Sardinia, fostering greater RES development and increased grid reliability. The TUN-ITA Link, planned for 2028, will integrate the European and North African transmission grids. This infrastructure is considered strategically important and provides an additional tool to optimize the use of energy resources between Europe and North Africa. The above factors make it possible to state that Terna has planned important investments for the Sicilian territory to keep the transmission grid secure and reliable in light of the increased installed capacity of RESs, according to the Fit-for-55 (FF55) targets [23] (Table 2).

Table 2. Increase in RES capacity in Sicily according to the Fit-For-55 scenario.

Source	Type	2022 [GW]	2030 (FF55) [GW]
Wind	Onshore	2.13	1.06
	Offshore	0	1.4
PV	Rooftop (LV)	0.63	1.06
	Utility Scale (MV, HV)	1.11	1.4

Nevertheless, the connection requests in Sicily for onshore wind and photovoltaic plants registered on 30 September 2023 amounted to 55 GW against an FF55 target of 8.68 GW. A significant aspect is the geographical distribution of the connection requests; in many cases, they are located in already congested areas (referred to as critical areas), where new assets will need to be built to achieve full integration. Planning the development of the grid, especially in areas characterized by a different distribution of RESs than assumed, is one of the critical issues related to the energy transition. A careful study of the evolution of the connection requests will allow for more interventions on some aspects of the grid compared to others, ensuring a more secure integration of renewable sources.

3. Methodology

The objective of this study is to determine how the Sicilian electric system will respond to the amount of wind and photovoltaic capacity installed before the grid infrastructure developments shown in Table 1 are completed in a short-term scenario. This study is based on the methodology succinctly shown in Figure 2.

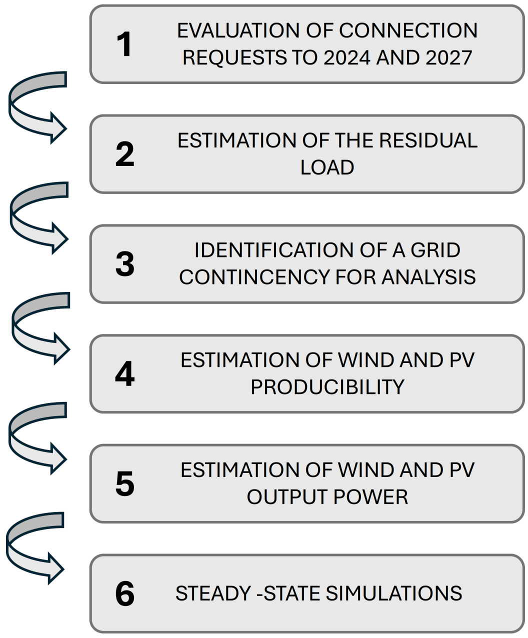

Figure 2. Workflow of the presented methodology.

3.1. Evaluation of Connection Requests for 2024 and 2027

Figure 3 shows the progress of connection requests for new photovoltaic and wind power plants to the Sicilian grid as of 30 September 2023. This study is conducted by looking at two scenarios: a current one in 2024 and a future one in 2027. The 2024 scenario is characterized by all requests where the producer has already signed the connection contract with Terna, indicating plants close to construction and subsequent grid connection. In addition to the generation introduced in the 2024 scenario, the 2027 scenario is characterized by plants with advanced authorization or construction status, as well as a percentage of plants at an early stage of construction that will evolve into advanced status over time. The percentage of early-stage installations was chosen based on the study of the progress of connection requests, which is 3% for photovoltaics and 5% for wind power.

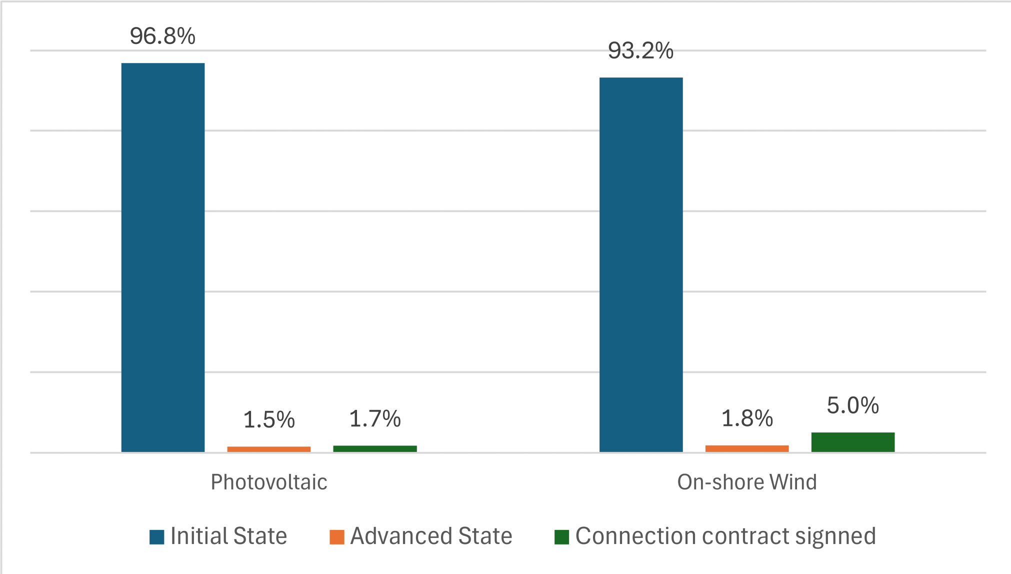

Figure 3. Distribution of the progress of connection requests by source as of 30 September 2023.

3.2. Estimation of the Residual Load

To estimate the power flowing on the transmission grid in the above-defined scenarios, it is first necessary to determine the photovoltaic capacity that will be installed and connected to the MV and LV distribution grids. In fact, in recent years, mainly due to the development of photovoltaic generation connected to the distribution grid, the HV load has gradually decreased. The difference between the load supplied by the distribution grid and the power produced by plants connected to the same grid constitutes the so-called residual load of the HV grid. The estimation of the generation connected to the distribution grid is conducted through an analysis of historical data. Since it is currently not possible to predict the introduction of new incentives, future installed capacity is estimated through a linear interpolation starting from historical data on installed capacity over the last ten years (2013–2022) [24]. Figure 4 shows the trend of the installed PV capacity at low and medium voltage levels. Values in orange were determined through linear interpolation with a 95% confidence interval.

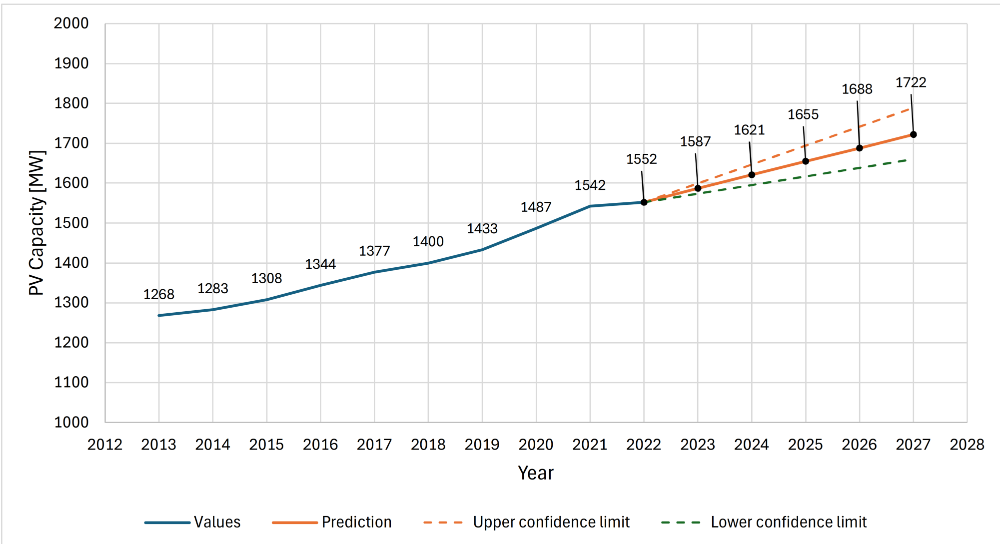

Figure 4. Estimation of the PV capacity installed on the distribution grid.

3.3. Identification of Significant Operating Conditions for Analysis

Regarding the operating conditions of the Sicilian power system to be analyzed, we chose two cases of significant criticality for the system:

- OC1: High load demand and imported power value close to the exchange capacity of the cable connecting Sicily with the mainland. This situation was recorded on 24 July 2023 at 4:45 p.m. (peak power 4474 MW) and is shown in Figure 5;
- OC2: Low load demand and high generation from RESs, with power exported to the mainland. This situation was recorded on 16 April 2023 at 3:30 p.m. and is shown in Figure 6 [25].

The two operating conditions, in some ways opposite, are suitable for the evaluation of the behavior of the electric system in the most critical cases:

- Congestion due to the saturation of line capacity;
- Significant renewable generation.

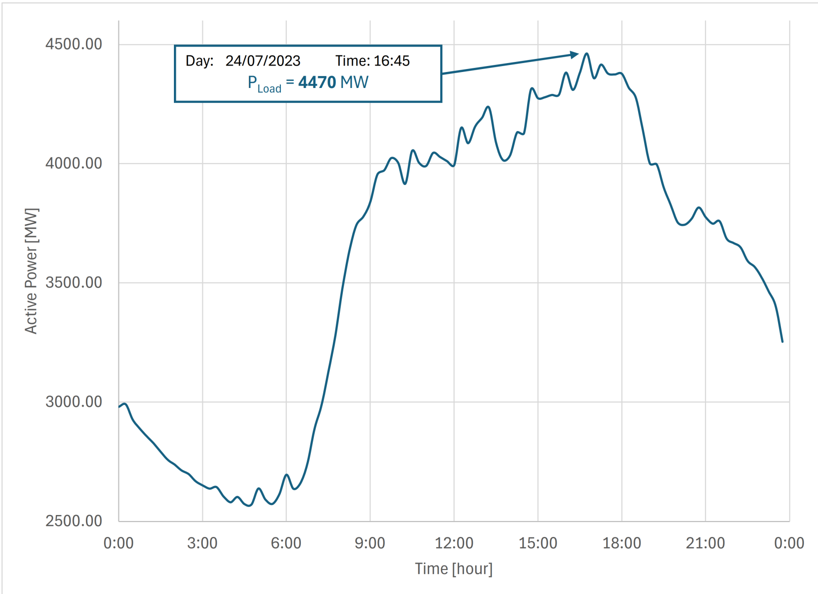

Figure 5. High load demand operating condition OC1 (24 July 2023).

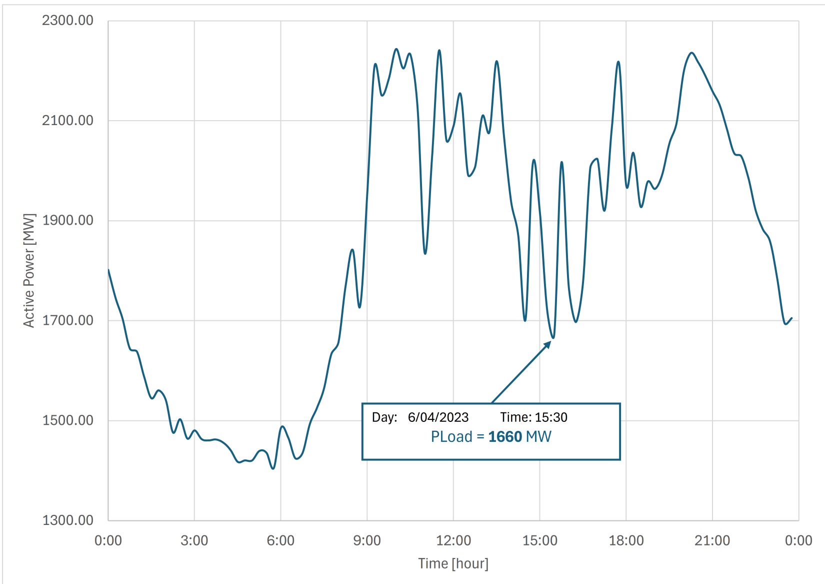

Figure 6. Low load demand operating condition OC2 (16 April 2023).

3.4. Estimation of Wind and PV Producibility

In order to quantify and subsequently place the power extracted from the analysis of connection requests appropriately in the simulation environment, it is necessary to study the producibility of PV and wind plants in Sicily. The procedure is as follows: Sicily is divided into two parts, eastern and western. For each area and each type of source, a reference plant is identified, as shown in Figure 7. Once the power output of the plants is known, divided by the nominal size, the dimensionless coefficients in Table 3 are obtained. As can be seen from the reported values, the coefficients related to PV exhibit greater variability concerning the operational conditions examined, while there are no significant differences regarding the geographical areas of interest. Regarding wind power, we observe the opposite behavior: while load conditions do not seem to decisively influence the coefficients, these coefficients are higher in the western region of the island, which confirms the greater potential of the area for wind energy production. Therefore, as a simplifying assumption, it is assumed that all wind and photovoltaic plants that fall within either region have the same producibility as the reference plants.

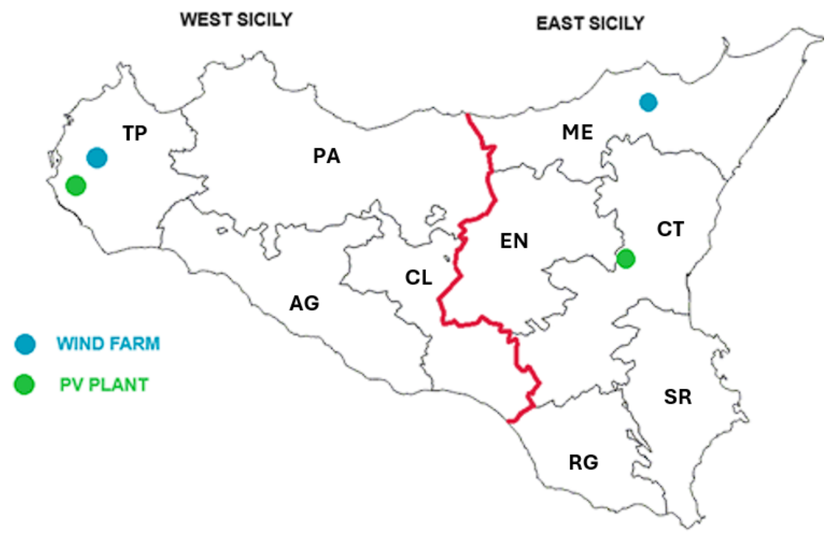

Figure 7. Partition of Sicily for estimating wind and PV producibility, the red line divides western Sicily from eastern Sicily

Table 3. PV and wind producibility. Coefficients are defined as the ratio between the power produced and the power installed in the reference PV or wind plants.

	PV Plants	
Operating Condition	**Western Sicily**	**Eastern Sicily**
OC1: High load	0.788	0.835
OC2: Low load	0.431	0.426
	Wind plants	
Operating condition	**Western Sicily**	**Eastern Sicily**
OC1: High load	0.341	0.194
OC2: Low load	0.585	0.231

3.5. Estimation of Wind and PV Output

Based on the progression of connection requests submitted to Terna, in accordance with the previous Section 3.1, the increases in RES capacity compared to 2023 are shown in Table 4. All the considered renewable sources show an upward trend starting from the coming years. Among them, however, the one that stands out the most is PV (photovoltaics), with an expected increase in installed power connected to both the distribution and the transmission grid of 1413 MW by 2027. This information alone briefly describes the significant stress conditions that the Sicilian grid is already facing, with an annual renewable penetration rate never recorded until now. Wind power, on the other hand, while growing at half the rate of PV, is almost entirely concentrated on the western coast of the island. This concentration could lead to potential challenges in managing production and distributing energy to consumption centers.

Table 4. Increase in RES capacity compared to 2023.

	2024 Scenario [MW]	2027 Scenario [MW]
PV connected to the LV/MV grid	+69	+170
PV connected to the HV Grid	+269	+1243
Wind	+345	+648

Finally, assuming the coefficients in Table 3, the actual power output is derived and reported in Table 5. The values in Table 5 are used to assess the impact of the increase in renewable sources in the steady-state analysis that is shown in the next sections. In 2024, the total production increase is equal to 410 MW in the high load condition and 460 MW in the low load condition, while in 2027, it is 1287 MW in the high load condition and 1200 MW in the low load condition. These increases should be considered significant when compared to the island's average load, which, according to the latest Terna statistics, is around 2800 MW [7].

Table 5. Increase in RES production compared to 2023.

	2024 Scenario [MW]		2027 Scenario [MW]	
Source	**High Load**	**Low Load**	**High Load**	**Low Load**
PV (on LV and MV grid)	+60	+98	+157	+148
PV (on HV Grid)	+222	+159	+939	+731
On-shore wind	+128	+203	+191	+321

4. Simulations and Results

The steady-state load flow calculations were carried out using WinCreso® software, developed by CESI in collaboration with Terna, and tested against the requirements of the Common Grid Model Exchange Standard (CGMES) of ENTSO-E [26]. The tool allows for the simulation and analysis of a power grid in steady-state operation, particularly power flow and N-1 security calculations, as well as the optimization of active and reactive power outputs. All parameters describing the operative conditions to be simulated were downloaded from Terna's servers. In addition to the grid topology, all the information needed to perform the static analysis is also provided, i.e., the power generated by each power plant, the power absorbed by each load, the status of the parallel busbar, and the positioning of the lines in the station busbars. In the following, for simplicity, the two operating conditions are referred to as OC1 high load and OC2 low load.

4.1. OC1: High Load

Table 6 shows the data used for the simulations in the 2023, 2024, and 2027 scenarios. Negative and positive values refer to production and load, respectively. On 24 July 2023 at 4:45 p.m., the highest-ever demand of 4474 MW was recorded. Due to the favorable weather conditions experienced, there was high power production from photovoltaic sources on the distribution grid, amounting to 1298 MW. Under these conditions, the HV load, i.e., the amount of power circulating on the transmission grid, was reduced to 3176 MW, which is precisely the power that the generating units connected to the HV grid had to cover. To balance the remaining portion of power that it could not cover internally, Sicily imported 1327 MW from the mainland. The production from wind and photovoltaic sources, calculated above for the 2024 and 2027 scenarios, was then introduced. A choice was made to reduce thermal generation to 1041 MW through the removal of some thermal generating units due to the desire to offset this removed power with that introduced through renewables. In the 2024 scenario, this choice brought exported power to the limit of the trading capacity. In the 2027 scenario, generation from renewable sources was driven by PV, which alone accounted for half the HV load. In addition, PV generation on the distribution grid increased by an estimated 97 MW compared to the 2024 scenario. Production from thermal sources remained unchanged, as did hydro production. Under these conditions, imported power from the mainland was reduced to 575 MW.

Table 6. Summary of the high load and imported power operating condition.

OC1: High Load			
Scenario	**2023 [MW]**	**2024 [MW]**	**2027 [MW]**
Total load	4474	4474	4474
PV prod. in LV/MV	−1298	−1358	−1455
HV load	3176	3116	3019
Thermoelectric prod.	−1589	−1041	−1041
PV prod. in HV	−85	−307	−1024
Wind production	−229	−347	−420
Hydroelectric prod.	−11	−11	−11
Grid losses	65	65	52
Import	1327	1474	575

Tables 7 and 8 report the line overloads detected through the simulations in WinCreso for the 2024 and 2027 scenarios, respectively. In the 2024 scenario, the contingencies occurred only in the eastern region of the island due to its high density of photovoltaic installations, leading to a risk of line overloads during periods of high production. However, these events should not be considered extreme, as the overloads were around 67% in the first case and 19% in the second case. In the 2027 scenario, however, the geographical location of the contingencies was substantially reversed: both detected events occurred in the western part of the island, an area that is expected to see a massive penetration of wind power installations in the near future. This highlights that in the coming years, the areas requiring intervention may change radically compared to the current state, making accurate planning of interventions necessary starting in the next few years.

Table 7. Summary of the 2024 high load and import operating condition simulation.

Contingency	**Description**
380 kV line in Messina area	After the tripping of the 380 kV line, the power is divided as follows: almost 70% goes to the interconnected 220 kV line, the remaining power to the 150 kV lines, overloading an autotransformer to 119%.
220 kV line in Catania area	The tripping of the 220 kV double circuit transmission line protections results in power splitting on the remaining 150 kV lines, leading to a single 106% overload in the Catania area.

Table 8. Summary of the 2027 high load and import operating condition simulation.

Contingency	Description
220 kV line in Trapani area	The loss of a 220 kV line in the Trapani area results in the following power split: half on neighboring 220 kV lines, half on other 150 kV lines, resulting in an overload of a line in their respective vicinity.
220 kV line in Trapani area	The tripping of this 220 kV line predominantly in the Trapani area, characterized by significant generation from wind and photovoltaic sources, determine the divergence of load calculus. This could mean collapse of the grid.

4.2. OC2: Low Load

Table 9 shows the low load and imported power applied in the 2024 and 2027 scenarios. On 16 April 2023 at 3:30 p.m., the total demand was 1992 MW, lower than the average load in Sicily. Due to sunny weather conditions and considerable winds, renewable sources covered almost all of the demand. With 847 MW of photovoltaic production on the distribution grid, the HV load was reduced to 1145 MW (covered entirely by 1154 MW from wind sources). The load was covered entirely by RESs, combined with thermal production at its technical minimum, guaranteeing the static stability of the grid and allowing 543 MW of power to be exported to the mainland. In the 2024 scenario, PV generation on the distribution grid increased by 98 MW compared to 2023, reducing the HV load to 1047 MW. In the 2027 scenario, the very high production from renewable sources brought the exported power to the mainland up to 1287 MW. PV generation on the distribution grid increased by an estimated 49 MW compared to the 2024 scenario and by 148 MW compared to the initial 2023 scenario. Production from thermal sources remained unchanged, while pumping from hydropower plants increased to 495 MW, as it is plausible that the extra power would be used for this purpose in a scenario of high production and low load.

Table 9. Summary of the low load and high exported power operating condition.

OC2: Low Load			
Scenario	**2023 [MW]**	**2024 [MW]**	**2027 [MW]**
Total load	1992	1992	1992
PV prod. in LV/MV	847	945	995
HV load	1145	1047	997
Thermoelectric prod.	−661	−661	−661
PV prod. in HV	−70	−229	−801
Wind production	−1154	−1356	−1475
Hydroelectric pumping	147	147	495
Grid losses	50	77	159
Export	−543	−975	−1287

Tables 10 and 11 report the line overloads detected through simulations in WinCreso for the 2024 and 2027 scenarios, respectively. In general, all contingencies were due to severe imbalances between generation and load. For example, low load periods were characterized by high production and low load, resulting in an increase in the power flowing in the lines in the directions of the connections to the mainland. In the 2024 scenario, two contingencies were detected: one on the ultra-high-voltage network at 380 kV and another on the high-voltage network at 220 kV. The first case involved poor power distribution, with local overloads of 40% compared to nominal values, while the second case involved the activation of protections on a backbone, causing a slight overload on the downstream network at 150 kV. The situation worsened significantly in the 2027 scenario, with three contingencies detected that were more severe than the previous ones. In all examined cases, the events were detected on the 220 kV network; however, the consequences affected the lower-voltage networks more severely compared to the 2024 operational condition. This essentially leads to two preliminary conclusions: first, the network will be subject to a higher number of extreme events starting in the coming years; and second, interventions on the ultra-high-voltage network only partially mitigate the contingencies, which manifest with greater intensity in the lower-voltage networks.

Table 10. Summary of the 2024 low load and high export operating condition simulation.

Contingency	Description
380 kV line in Messina area	The contingency results in the division of power in the following manner: 81% of the power redistributes to a neighboring 380 kV line, causing it to be overloaded to 140%; the remainder to the lines at lower voltage levels.
220 kV line in Ragusa area	The tripping of the 220 double circuit transmission line protections results in power splitting on the remaining 150 kV lines, leading to two overloads over 110%.

Table 11. Summary of the 2027 low load and high export operating condition simulation.

Contingency	Description
220 kV line in Palermo and Messina areas	The tripping of the double circuit transmission line protections results in power splitting on the remaining 150 kV lines, leading to three overloads over 140% and 4 over 100%.
220 kV line in Ragusa area	This contingency causes 2 overloads over 160% and 6 overloads over 110% in some 150 kV afferent lines.
220 kV line in Trapani area	The tripping of the 220 kV line protections results in power splitting on the remaining 150 kV lines, leading to an overload over 140% and 7 over 100%.

5. Discussion

The simulation results show critical situations even in near-future scenarios, where the development of renewables is not expected to be comparable to that projected for 2030 or 2040. During a high import situation (OC1), increasing internal generation reduces the exchange with the mainland, and the 380 kV lines, which are in close proximity to the exchange points with the continent, do not experience overloads as a result of contingencies. However, as internal generation increases, line trips can occur where renewable generation is higher. Under the theoretical assumption of no countermeasures, this could cause a failure in redistributing power to neighboring 220 kV and 150 kV lines or even the collapse of the system. During a high export situation (OC2), increasing internal generation with the same load can only result in increased exported power. This aspect highlights the importance, especially for Sicily, of introducing new lines to export the surplus power generated by RESs in the future. For this reason, the Tyrrhenian Link and the TUN-ITA HVDC Link are currently being realized. In a strong export situation, as internal generation increases, contingencies on lines where renewable generation is important can cause severe impacts on other 220 kV and 150 kV lines, with no available countermeasures. Particularly exposed to this type of contingency are the 150 kV lines in the Ragusa area, which come under significant stress in the case of power outages on the 220 kV double-circuit transmission line that characterizes the coastal ring. A similar argument can be made for the loss of the 220 kV line in the Trapani area.

6. Conclusions

From the study and analyses conducted, it has emerged that the increasing integration of renewable energy sources, which are crucial in the energy transition process currently underway, will soon result in the tightening of grid operating conditions. In addition, the reduction in short-circuit power at grid nodes, as a main consequence of the decommissioning of conventional thermal plants in favor of inverter-based plants, increases the depth of voltage dips in the event of failure. In the two operating conditions analyzed—high load and low load—well-defined patterns have been identified. Starting in 2027, the grid's stress conditions will increase in number and intensity, with more severe consequences for downstream lower-voltage networks. Several overloads were detected, reaching up to 140% of the available nominal power and, in one isolated case, even 160%. This underscores the need to enhance not only the main extra-high-voltage lines but also the branches near production centers. Finally, another crucial piece of information that has emerged from the analyses concerns the location of contingencies, which were found in close proximity to production centers due to the imbalance between renewable energy production and demand from the load. Although in the 2024 scenario these were concentrated in eastern Sicily, which was more affected by the presence of photovoltaic plants, four out of the five contingencies identified in the 2027 scenario were located in western Sicily, which will experience a significant penetration of wind farms in the coming years. This clearly indicates that to address the stress the grid will face in the coming years, it is necessary to intervene at the provincial level. Priority should be given to the aforementioned provinces to avoid local overloads and the curtailment of renewable energy.

The benefits of infrastructure development involving higher transit limits not only increase transmission capacity but also ensure greater flexibility in system management and greater efficiency in terms of the outcome of the energy market. One example is the implementation by 2028 of the Tyrrhenian Link, which will ensure the adequacy of the electricity system in light of the expected decommissioning of the oldest and most environmentally impactful plants. This allows for better penetration of renewable generation, limiting curtailment phenomena and reducing costs in the energy market, dispatching services, and grid congestion. However, the frequency and intensity of extreme weather events, coupled with the decommissioning of the traditional generation fleet, may lead the grid into uncertain and risky operating conditions, necessitating new electricity system management logic and major grid infrastructure reinforcement. Finally, beyond the specific results of the Sicilian network study, this article proposed a short-term analysis methodology that can be applied in similar studies in different contexts.

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