Load-Flow studies on the Future Power Grid of Sicily: Analysis of 2030 Scenarios

Rossano Musca
University of Palermo
Palermo, Italy
rossano.musca@unipa.it

Eleonora Riva Sanseverino
University of Palermo
Palermo, Italy
eleonora.rivasanseverino@unipa.it

Antony Vasile
University of Palermo
Palermo, Italy
antony.vasile@unipa.it

Gaetano Zizzo
University of Palermo
Palermo, Italy
gaetano.zizzo@unipa.it

Adriano Iaria
RSE SpA
Milano, Italy
adriano.iaria@rse-web.it

Angelo L'Abbate
RSE SpA
Milano, Italy
angelo.labbate@rse-web.it

Lorenzo Vitulano
RSE SpA
Milano, Italy
lorenzo.vitulano@rse-web.it

***Abstract*— This paper presents the results related to load-flow studies of the Sicilian power grid in different 2030 scenarios. The analyzed scenarios incorporate data elaborated by RSE and University of Palermo as well as publicly available data from Terna databases. These datasets have been processed in order to consider the forecasted development of loads and renewable resources in Sicily. The model of the Sicilian power grid used for simulations developed in Neplan environment has been used: it incorporates the information regarding the infrastructures under authorization and realization by 2030. Simulation outcomes indicate that the Sicilian power grid will experience significant active power flows from renewable generation, leading to local congestion, overloading of some key transformers, and utilization of several transmission lines over 70% of their capacity. These results indicate that the integration of renewable energy generation in the Sicilian power grid poses challenges that will be even more severe in the years to come: this detection represents an important first outcome, to be handled by selecting appropriate solutions.**

Keywords—Load-Flow, Sicilian grid, renewable penetration, scenario analysis, transmission system planning and operation.

I. INTRODUCTION

The electric power sector is experiencing a major transition to a renewable-based and decarbonized model. In recent years, there has been a remarkable growth in global renewable power plants installations, driven by technological advancements, cost reductions, and supportive government policies. This global trend is expected to continue and even accelerate in the coming years, leading to a substantial increase in the share of renewable energy in the power mix in Italy and in Europe [1], [2]. Italy's geographical location and conducive climate conditions make it well-suited for solar and wind energy generation. The country, however, extends more in the North-South direction, making the availability of renewable energy greatly different between northern and southern areas: as a result, there is a larger number of installations in the South of the country and the two major islands, Sicily, and Sardinia [3]. Given its strategic location, Sicily is the object of a broad attention from all actors in the power system, which makes it the perfect candidate as an Energy Hub for the Mediterranean Area [4]. The great availability of renewable energy sources (RES) is reflected in the large number of connection requests received [5]. However, this raises a crucial issue since the majority of Italian industrial facilities, with the most significant amounts of electric loads, are located in the northern part of the Country. Therefore, in the coming years, an unequal repartition between the location of RES generation and that one of demand will emerge. This can put transmission corridors along the north-south tie axes under heavy loading, leading to grid congestions as well as over-generation and energy curtailment for several hours per year in more regions and zones: this is the case for Sicily too. This would reduce the savings in terms of emissions and extend the time for return on investments in RES power plants. Over the next few years, several reinforcements to the Sicilian grid have been planned to be realized by Terna, the Italian TSO (Transmission System Operator) [6]; the aim consists in both ensuring the integration of the numerous wind and photovoltaic plants being planned and enhancing interconnection with the other Italian regions and with foreign countries. This paper, resulting from a framework collaboration between the Italian energy research company RSE (Ricerca sul Sistema Energetico) and the University of Palermo, aims to present some load-flow studies on the Sicilian grid in 2030 scenarios. The investigation has been conducted based on a previously validated model of the Sicilian grid as of 2022 [7]-[11], implemented in Neplan environment: this model has been expanded to include the planned interventions for 2030 and the estimated load and generation evolutions to 2030. These have been based on reference scenarios identified and on these scenarios the load-flow studies have been conducted. The following sections provide a brief description of the network model, the analysed 2030 scenarios, and the obtained results. From the results, it can be highlighted that in the analysed 2030 scenarios the Sicilian grid may experience stressed condition, with localized congestions and, in some cases, transformer and line overloads during several hours of the year.

II. SICILIAN GRID MODEL AND PLANNED IMPROVEMENTS

The model of the Sicilian power grid was developed in the Neplan 360 environment through several collaborations between the University of Palermo and Terna SpA over the years [7]-[11]. The model has been constantly updated, considering Terna's development plans and information gathered through collaborations with various stakeholders, such as petrochemical hubs companies or private companies investing in large renewable power plants in Sicily. It also considers documents freely available for consultation on the website of the Ministry of Ambient and Energetic Security (MASE, [12]), known in the previous government as Ministry of Ecological Transition (MiTE). The grid model updated to 2022 includes:

- overhead and underground transmission lines of the Sicilian network at 380 kV, 220 kV, 150 kV, and 60 kV;
- transformation substations at 380/220 kV, 220/150 kV, 150/60 kV, and 150/20 kV;
- thermal power plants and pumped storage power plants in the Sicilian network, including models of speed regulators;
- the electrical storage system in the busbar of Ciminna;
- synchronous compensators in the busbars of Partinico and Favara;
- electric loads at the respective voltage level;
- photovoltaic and wind generators.

The model is connected to an equivalent generator of the European network, whose dynamic behavior has been determined using the Initial Dynamic Model provided by ENTSO-E [13]-[14]. The network model is updated considering the interventions listed in Table I that represent all the 2030 network reinforcement projects as reported in the development plan edited by Terna [6]. Further details are highlighted in Fig. 1 that shows the proposed, planned and under realization interventions on the Sicilian power grid.

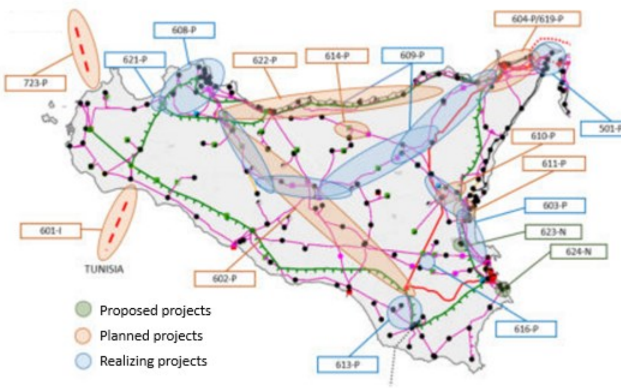


Fig. 1. Interventions planned in Terna's development plan [6].

In the implementation of the new network layout, the connection of the Tyrrhenian Link East (TLE) to the Montecorvino power station in Italian Mainland (Campania region) is assumed as part of the equivalent station representing the entire continent, with the downstream network modelled through a synchronous generator and a load. As for the TLE, the downstream network of the Selargius station, in Sardinia, is also modelled as a synchronous generator along with three loads. The presence of loads next to these generators does not affect the load flow study but it is useful in dynamic studies to simulate the disconnection of loads in the Continental Europe (CE) area or in Sardinia. The downstream system of Tunisia is represented as a node that does not participate in the dynamic simulations of the network. The offshore wind farms currently under authorization or construction are represented as nodes connected to network nodes through cables, whose technical characteristics (length, capacity, resistance, and reactance) have been determined from the freely downloadable project documents available on the MASE website [12]. In cases where this information is not available, the wind farms are represented as generators directly connected to the nearest 220 kV node of the Sicilian network along the coast in the province where the wind farm is located.

TABLE I. COMPLETE LIST OF SCHEDULED INTERVENTIONS IN SICILY TO 2030 [6].

Code	Name
555-N	New 380 kV "Bolano – Paradiso" connection
601-I	New "Italy – Tunisia" interconnection
602-P	380 kV "Chiaramonte Gulfi – Ciminna" power line
603-P	380 kV "Paternò – Pantano – Priolo" power line
604-P/619-P	380 kV "Assoro – Sorgente 2 – Villafranca" power line
607-P	220 kV "Partinico – Fulgatore" Power Line
608-P	Palermo's Metropolitan Area Restoration
609-P	HV Lines general interventions for renewable integration
610-P	Line 150 kV "Paternò – Belpasso"
611-P	Interventions on the HV network in the Catania area
612-P	Interventions on the HV network in the northern area of Catania
613-P	Interventions on the AT network in the Ragusa area
614-P	Removal of the 150 kV Castel di Lucio rigid branch line
616-P	380 kV Vizzini substation (ex SE 380 kV Mineo)
621-P	Partinico 220 kV station
622-P	150 kV line "SE Caracoli – SSE Furnari RT"
623-P	New 150 kV power line "Lentini – Lentini RT (ex FS)"
624-P	New 150 kV junction "CP Siracusa est – CP Siracusa RT (ex FS)"
625-P	Rationalization of the HV network in the Caltanissetta area
626-P	New 150 kV power line "Vallelunga RT – SE Cammarata"
627-P	380 kV "Caracoli – Ciminna" power line
628-N	Meshing interventions in the industrial area of Catania
629-N	Rationalization of the Cefalù area
630-N	Island of Favignana interconnection
632-N	Mesh increase 150 kV Trapani area
723/E-P	HVDC connection "Sicily - Mainland (Tyrrhenian Link East)"
723/W-P	HVDC connection "Sicily - Sardinia (Tyrrhenian Link West)"

III. SIMULATED 2030 SCENARIOS

The 2030 scenario was developed with the objective of evaluating alternative decarbonization pathways that, while achieving the same reduction in greenhouse gas emissions as the Fit-for-55 (FF55) package [15], can foster the development of industrial facilities, protect the international competitiveness of Italian companies, as well as contain the social cost of the transition. For each scenario, RSE provided hourly load and production profiles as well as utilization profiles of electrochemical storage systems, electrolyzers, and pumping stations for a full year of operation of the Sicilian grid. Table II reports a summary of the main data for the considered scenario.

Different operating conditions of the Sicilian network in 2030 scenario have been identified for the purpose of this study. These conditions refer to key critical situations as reported in the following:

- **S.0 MAX GEN-LOAD OG**: maximum difference between generation, both traditional and non-traditional, and the load of the island with overgeneration (OG). In this operating condition, power flows through the transmission lines connecting Sicily to other areas exceed the total capacity of the interconnections, so curtailment of renewable generation should be implemented. However, in the simulations, the renewable's production is not curtailed in order to test the system's performance under highly critical circumstances.

- **S.0 MAX GEN-LOAD**: maximum difference between generation, both traditional and non-traditional, and the load of the island without OG. In this operating condition, there is the maximum difference between generation and load, but curtailment of renewable generation is not required. This operating condition is more realistic than the previous one and represents the most critical situation in which the system can realistically operate.
- **S.1 MAX THERMO**: maximum power production from traditional and cogeneration thermal power plants.
- **S.2 MAX RES**: maximum power production from renewable sources without OG. Simulating this operating condition allows testing the limits of the network in the presence of maximum renewable generation in the Extra High Voltage (EHV)/High Voltage (HV) grid.
- **S.3 MAX LOAD:** peak hour of the Sicilian load.
- **S.4 MAX IMPORT:** hour with the maximum value of energy import into Sicily from other interconnected areas.

TABLE II. ENERGY SCENARIO FOR THE SICILY FOR 2030.

Rated power of generation units [GW]		**Electric Load**	
Gas	3.516	Total annual demand [TWh]	21.1
Other Non-RES	0.452	Total annual demand for H production [TWh]	1.57
Solar (of which CSP)	6.011 (0.550)	Max Load without electrolysers [GW]	3.59
Onshore Wind	4.317	Min Load without electrolysers [GW]	1.41
Offshore Wind	1.218	Max Load with electrolysers [GW]	4.34
Hydro	0.765	Min Load with electrolysers [GW]	1.44
Biomass	0.084	Max electrolysers load [GW]	1.15
Storage	0.612		
Power-to-X	1.200		

Once the scenarios are defined, the date and time at which the reported condition occurs are determined. In order to perform load-flow simulations in each selected time instant, the first step consists in the estimation of load and renewable generation for each of the nine provinces on the island. This estimation is carried out from zonal analysis on a provincial basis, after which the calibration of generators is executed, and the load data are allocated. Subsequently, the system is balanced by defining the power flows in the interconnections to and from Sicily, then load-flow simulations are performed using the extended Newton-Raphson method. Figure 2 shows the Load-Gen balance for each of the scenarios under examination. If load-flow convergence is achieved, voltage profiles at the nodes of the three voltage levels present in the EHV/HV system (400 kV, 220 kV, and 150 kV) are evaluated, along with the load factor of all transformers and transmission lines.

IV. SIMULATION RESULTS

The present section summarizes the key results of the load flow analysis. In some cases, severe conditions are detected for the Sicilian power grid in the analysed 2030 scenario cases. Fig. 2 shows the result of the Load-Gen balance in each of the scenarios under examination. It can be observed how Sicily is subject to large power fluctuations depending on the operating condition, with a maximum export of 5005.63 MW in the S.0 OG scenario and a maximum import of 2773.03 MW in the S.4 scenario.

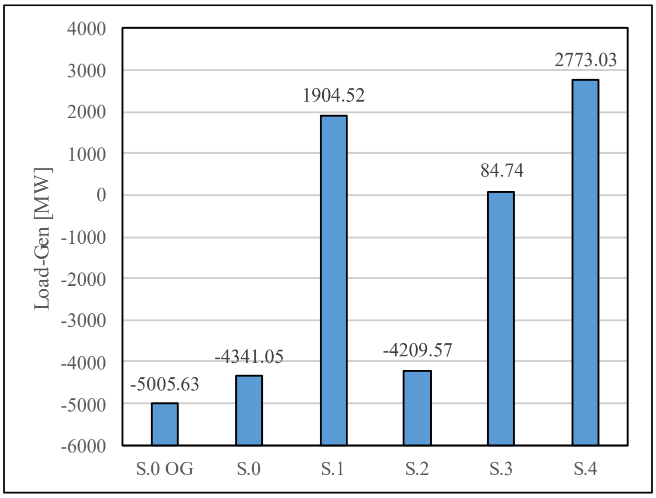
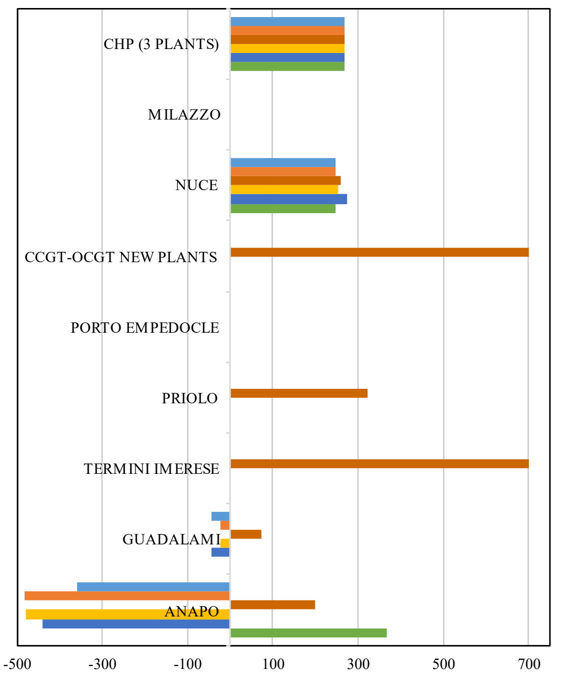


Fig. 2. Load-Gen in Sicily for each analyzed scenario at 2030.

For each operating condition, Fig. 3 reports the production from hydro and thermal power plants on the island, while Fig. 4 provides details on interconnections with other regions in Italy and with Tunisia and Malta. Some important statements can be inferred from these figures: with the exception of the S.1 MAX THERMO scenario, production from fossil sources is almost totally excluded from the energy mix, with the only active thermal power plants being Nuce and three CHP plants, which together produce a maximum of 541.29 MW. Also noteworthy is how, in four out of six scenarios, the Anapo pumping facility behaves as a load (negative production).

From the perspective of interconnections, moreover, it can be seen that in most cases the AC and DC links export power outside Sicily. The Tyrrhenian Link, with its two East and West connections, will be a crucial infrastructure for the development of the Sicilian transmission grid and will ensure better integration of RES power plants on the island. Among the connections investigated, the cases of the Malta-Sicily and TUNITA links are emblematic: in all the scenarios analyzed, including those of maximum load and maximum import, the power flow through them is from Sicily to Malta and Tunisia respectively, indicating that the import condition from the two countries occurs only for a very small part of the year.

The most severe operating condition among those analyzed is S.0 OG. In this configuration, in fact, the grid experiences the maximum difference between load and generation with the latter being affected by energy curtailment due to saturation of the lines in proximity of the power plants. Fig. 5 shows the results of the load flow analysis. In particular Fig. 5.a shows the loading factor of the lines, Fig. 5.b the loading factor of the transformers, and Fig. 5.c the voltage value at the nodes as a percentage of the rated voltage. What can be observed from the graphs is a good distribution of voltage profiles that, in no case, exceed the ±5% threshold. The main problems emerging from the trends concern lines and transformers: the number of components with a loading factor greater than 75% consists of 70 lines and 9 transformers, with theoretical peaks of 350% of rated load. Experiencing the most overloaded conditions is the 150-kV network, while the 220-kV and 400-kV networks do not register any particular congestion, suggesting how a possible solution to the problem should involve upgrading interventions in the immediate proximity of production centers and not in the main ridges.

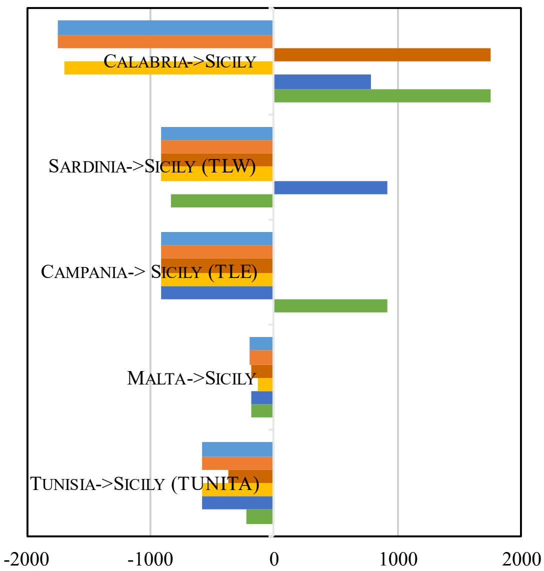


	ANAPO	GUADALAMI	TERMINI IMERESE	PRIOLO	PORTO EMPEDOCLE	CCGT-OCGT NEW PLANTS	NUCE	MILAZZO	CHP (3 PLANTS)
S.0 OG	-360.49	-44.8	0	0	0	0	247.7	0	268.2
S.0	-482.64	-22.4	0	0	0	0	245.98	0	268.2
S.1	200	73	702.38	323.46	0	702.38	258.77	0	268.2
S.2	-478.47	-22.4	0	0	0	0	253.24	0	268.2
S.3	-441.46	-44.8	0	0	0	0	273.09	0	268.2
S.4	367.2	0	0	0	0	0	246.66	0	268.2

Power Injection [MW]

S.0 OG S.0 S.1 S.2 S.3 S.4

Fig. 3. Hydro and Thermal Production in Sicily per Scenario by 2030.



	TUNISIA->SICILY (TUNITA)	MALTA->SICILY	CAMPANIA-> SICILY (TLE)	SARDINIA->SICILY (TLW)	CALABRIA->SICILY
S.0 OG	-574.98	-193.2	-916	-916	-1750
S.0	-574.98	-193.2	-916	-916	-1750
S.1	-365.57	-176.1	-916	-916	1750
S.2	-574.98	-129.8	-916	-916	-1693.34
S.3	-574.98	-183.6	-916	916	788.25
S.4	-218.89	-180	916	-826.14	1750

Power exchange [MW]

S.0 OG S.0 S.1 S.2 S.3 S.4

Fig. 4. Interconnections power exchange per scenario by 2030.

The same simulations were repeated for all the scenarios presented in Section III, the results relating to the loading factors of lines and transformers are presented in aggregate form in Figures 6 and 7 respectively, while Table III reports the registered node voltages per scenario and voltage level.

All things considered, the electricity grid is quite robust, the most onerous condition is represented by the S.0 scenario despite the absence, this time, of overgeneration. Overload events on lines are reduced compared to the S.0 OG scenario in all cases examined with percentages of -38% in scenarios S.0 and S.2, and even -100% in scenarios S.1, S.3, S.4. As far as transformers are concerned, however, there is a 22% increase in overload events in scenarios S.0 and S.2, with lower peaks in absolute value. Finally, as regards voltages, the only anomalies in the percentage values with respect to the nominal value are found in scenario S.3. In the time instant of maximum load, in fact, the voltage profile of some nodes of the 150 kV and 220 kV grids reaches values below the tolerance margin of ±10%. In particular, there are 39 nodes below 90% of the nominal value of 150 kV, with a minimum peak of 84% in 2 cases, while there are 2 nodes at 220 kV with a voltage between 89% and 90% of the nominal.

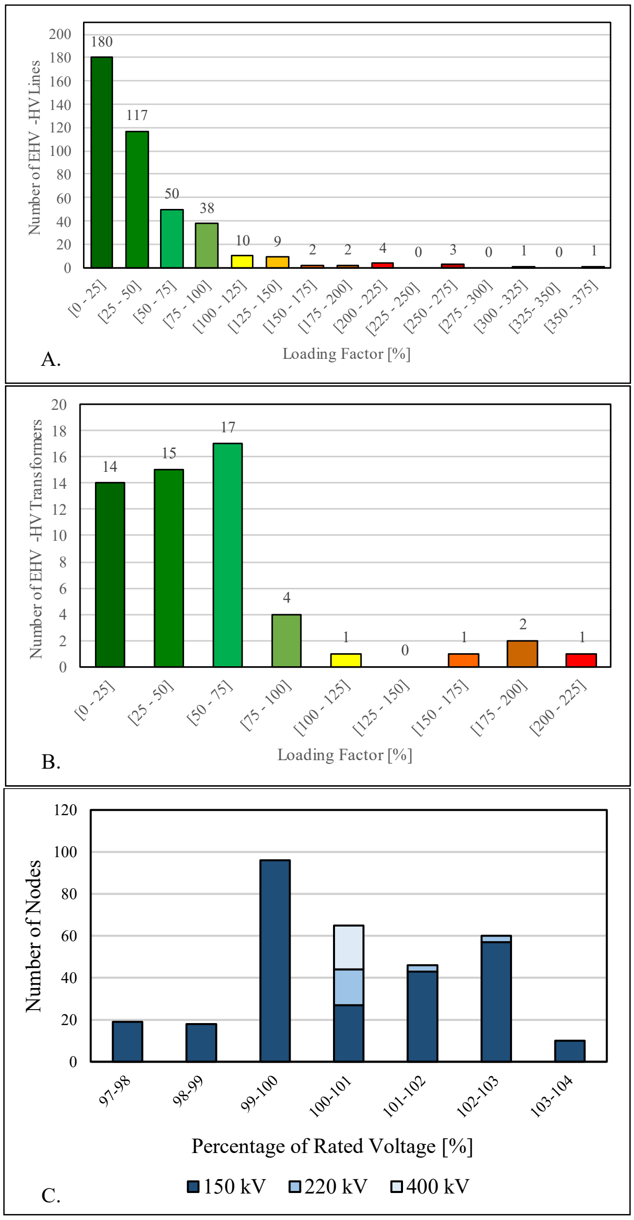


Fig. 5. Simulation Results in the S.0 OG Scenario: Lines Loading Factor (a), Transformers Loading Factor (b), Node Voltages (c)

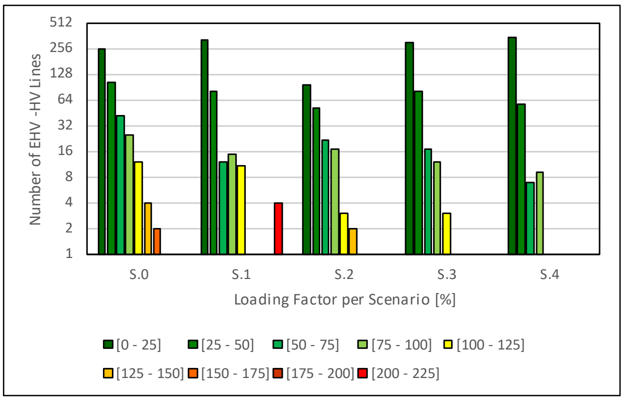


Fig. 6. Power lines loading factors per scenario by 2030.

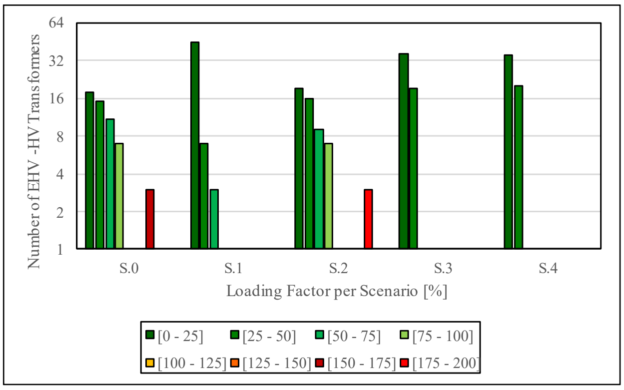


Fig. 7. Transformers loading factor per scenario by 2030.

V. CONCLUSIONS

The analysis of the results of the LF calculations in the 2030 operating configurations leads to interesting considerations on the scenarios hypothesized by RSE, which allow important conclusions to be drawn on the behavior of the Sicilian grid. Starting from 2030, the power system will be affected from flows of active power from renewable generation capable of causing local congestion, overloading several transformers and lines over 70% of their capacity. An upgrade of the grid to 400 kV does not produce significant benefits, suggesting that an intervention on the backbones near the production centres could have a greater impact in resolving congestion. The distribution of voltages is good in almost all scenarios but requires local interventions in some nodes where there are excesses of generation or load. The interconnections from Sicily to other Italian regions and foreign countries make a fundamental contribution in the hours in which the difference between the power generated and that required by the loads and storage systems is at its maximum but, from what emerges from the simulations, they are not sufficient to solve the problems related to overgeneration and congestion. Therefore, it is evident that, since the transport capacity of the power lines towards areas outside Sicily is saturated, it will be necessary to resort to different solutions in order to avoid congestion of the 150 kV grid and of the 220/150 kV transformers. The solutions under study include the use of HVDC or MVDC power lines to regulate the flows of active and reactive power in the most critical areas, the strategical management and installation of hydrogen electrolysers, and the use of electrochemical storage systems combined with PV and wind plants to level the power profiles in the transmission lines associated with these plants. Future studies, currently ongoing, will focus on these solutions and on the dynamic behaviour of the islands, also considering the contribution of the VSC converters of TUNITA and TL to the frequency regulation.

TABLE III. NUMBER OF NODES PER SCENARIO AND PERCENTAGE OF RATED VOLTAGE.

	S.0			**S.1**			**S.2**			**S.3**			**S.4**		
Voltage %	**150 kV**	**220 kV**	**400 kV**	**150 kV**	**220 kV**	**400 kV**	**150 kV**	**220 kV**	**400 kV**	**150 kV**	**220 kV**	**400 kV**	**150 kV**	**220 kV**	**400 kV**
84-85	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0
85-86	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0
86-87	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0
87-88	0	0	0	0	0	0	0	0	0	13	0	0	0	0	0
88-89	0	0	0	0	0	0	0	0	0	8	0	0	0	0	0
89-90	0	0	0	0	0	0	0	0	0	9	2	0	0	0	0
90-91	0	0	0	0	0	0	0	0	0	31	0	0	0	0	0
91-92	0	0	0	0	0	0	0	0	0	18	3	0	0	0	0
92-93	0	0	0	0	0	0	0	0	0	5	1	0	0	0	0
93-94	0	0	0	0	0	0	0	0	0	10	1	4	0	0	0
94-95	0	0	0	4	0	0	0	0	0	15	0	3	0	0	0
95-96	0	0	0	3	0	0	4	0	0	26	0	0	2	0	0
96-97	0	0	0	7	0	0	24	0	0	53	4	0	2	0	0
97-98	18	0	0	66	0	0	64	0	0	10	5	3	34	0	0
98-99	27	0	0	63	0	0	52	0	0	45	2	9	70	0	0
99-100	93	0	0	93	8	0	64	20	21	18	5	2	76	0	0
100-101	25	17	21	34	15	21	45	3	0	0	0	0	86	22	18
101-102	42	3	0	0	0	0	17	0	0	0	0	0	0	1	3
102-103	55	3	0	0	0	0	0	0	0	0	0	0	0	0	0
103-104	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0

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