The impact of large renewable deployment on electricity high voltage systems

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SUMMARY

In the last decades an increasing integration of renewable energy sources (RES) in the extra high voltage (EHV) and high voltage (HV) networks, boosted by technical reasons and political decisions has been noticed. RES introduce significant environmental benefits, but also considerable difficulties to power system planning and operation. In fact, if RES are correctly allocated, they allow deferring network upgrade investments and decreasing Joule losses. On the other hand, the uncertainty of RES production may cause dispatching problems, malfunctioning of protection and voltage regulation systems, etc. Many European Union (EU) research projects concluded that RES might be useful to accomplish economic, environmental and reliability targets removing the existing barriers to innovation and liberalized market.

The paper is part of a Research Project financed by the European Commission[2] to study the influence of a large penetration of RES on the EHV and HV electrical grids. The case study proposed in the paper refers to a portion of the Italian grid, the Sardinian power system, interconnected to the Italian mainland by means of the existing 200 kV and 500 kV high voltage direct current (HVDC) submarine cables (SA.CO.I. and SA.PE.I). Sardinia is one of the most favorable Italian regions for the exploitation of wind and solar energy and it has been experiencing a great increment of wind power production, which will be doubled in the next ten years. In the paper, the models to predict at 2020 and 2030 the generation park, demand profiles, as well as the development of the electricity infrastructures in Sardinia are briefly described. The steady-state analysis of the Sardinian grid with AC Power Flow studies applied to the foreseen load and generation scenarios in 2020 and 2030 allowed identifying critical conditions of the grid caused by RES production, load profile, and the lack of homotheticity between generation and load.

KEYWORDS

Renewable energy resources, High Voltage electrical grid, Sardinian power system.

INTRODUCTION

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[1] The views expressed in the paper are purely those of the authors and may not in any circumstances be regarded as stating an official position of the European Commission.

[2] "NL-Petten: Study on the impact of Large Renewable Deployment on European Electricity Higher Voltage Systems", European Commission JRC-Institute for Energy, Petten, INESC Porto Power Systems, 2009.

The evolution of the HV electricity transmission and LV-MV distribution grids is expected to be mainly guided by the large diffusion of distributed energy resources (DER), defined as small-sized power demand and supply-side devices, such as distributed generation (DG, in particular RES-based units) and storage/conversion technologies (including electric vehicles). RES-based units for electricity generation include wind farms, solar power arrays, and other energy forms, such as marine.
Integration of moderate quantities of RES can be positive for system operation, due to its inherent distributed nature, leading to loss reduction and improvements in the voltage profiles of the network. However, in scenarios where large RES generation facilities are built, namely when far from the main urban consumption areas, long distance power transmission infrastructures are required, an increase in active losses takes place and some additional difficulties in local voltage control may arise. For large scale deployment of RES (typically above some hundreds MW), a surplus of renewable energy from RES may take place, namely during valley load hours. In these cases, complementary active demand side measures can be adopted to increase electricity consumption during valley hours. Electric vehicles to grid will also have a favorable effect, if smart charging stations are used to flat the load pattern.
The aim of the paper is to improve the current knowledge about the influence of a large penetration of RES in the electricity grid. This is achieved by studying the electricity grid evolution in the Italian island of Sardinia. Sardinia is a good case study, with limited interconnections to mainland, relatively high solar and wind power availability, and viable options for further interconnections with North Africa and Europe. The analysis of the Sardinian electricity grid is based on a steady-state modeling for the years 2020 and 2030. Firstly, the RES penetration in the Sardinian power system at years 2020 and 2030 and modifications to the conventional power generation park has been forecasted as well as the expected changes of the load profile. Secondly, network congestions, critical assets and solutions to allow the integration of high share of RES have been achieved with the aid of power flow studies.

THE SARDINIAN TRANSMISSION GRID

The Sardinian transmission grid (Fig. 1) is approximately constituted by 4000 kilometers of lines, owned by the Italian TSO *TERNA*. The power system comprises transmission lines at 380-220-150 kV. The 380 kV EHV transmission network from North to South of Sardinia connects the two areas with the biggest power plants and a shorter 380 kV EHV line connects the two HVDC stations.
Sardinia is connected to the Italian mainland through the 200 kV 300 MW HVDC cable link called SA.CO.I. (Sardinia – Corsica – Italy), built in the middle of Sixty's and characterized by a limited transmission capacity and poor operation flexibility. From 2011, the bipolar ±500 kV 1000 MW HVDC submarine connection between Sardinia and mainland (SA.PE.I.) has been put into service.

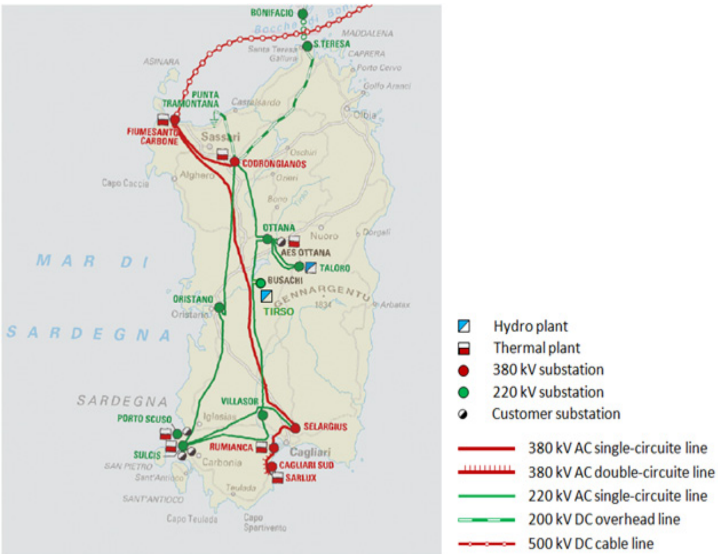

Fig. 1 - The Sardinian transmission grid

LOAD DEMAND IN SARDINIA

The consumption of electricity in Sardinia in 2008, last consistent data at the beginning of the study and quite stable also in 2009, reached 11935 GWh (excluding power transmission losses, auxiliary power plant consumption, hydro pumping and exchanges through the interconnections with the mainland), which corresponds to an electricity demand of 7154 kWh per person, demonstrating an increase of 12% compared to 1998. The peak demand in Sardinia that year was 1825 MW, registered in August. This is somewhat lower than the highest peak load ever registered, 1953 MW on 26th January 2006. That proves the change in the Italian trend of the electrical consumption: the maximum peak load has been often registered during summer instead of winter, due to the high use of air conditioners. Figure 2 shows four different daily load curves observed in 2008, for different seasons. The maximum peak load appears around 8-9 p.m. during summer, and the minimum valley load around 3-4 a.m. during winter. Hereof, average summer peak and winter valley load data are chosen for this study in order to create challenging conditions for grid operation with high RES shares.

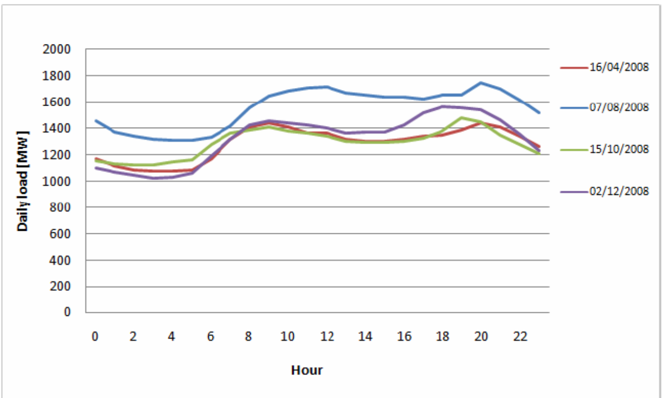

Fig. 2 - Seasonal daily load profile in Sardinia

POWER GENERATION IN SARDINIA

The energy production in Sardinia is dominated by thermal plants, coal and oil fueled, which covers more than 90% of the total Sardinian electricity generation (4218.8 MW in 2008, 4% of the total Italian generation capacity). Other energy sources include hydropower (4.5%) and biomass (4.3%). Due to the characteristics of the Sardinian territory, the hydro generation capacity is very limited and the potential is considered almost entirely exploited.

Sardinia is one of the most favorable Italian regions for the exploitation of RES (wind and solar energy) [1, 2]. In the last five years there has been a great increase total installed capacity of wind power plants, which is planned to be doubled in the next ten years [3]. In Sardinia the typical wind farm size is over 20 MW, with the latest projects that reach 100 MW.

Photovoltaic (PV) power plant capacities do not usually exceed 10 MW, with many plants smaller than 1 MW. Their contribution to the electricity production in Sardinia is very small (less than 1%) if compared with the other technologies. The Italian feed in tariffs is causing an impressive growth of the PV integration in the power systems with reference to the number of power plants and power capacity [4], and consequently the contribution of PV production is also dramatically increasing.

PV plants are connected to the low voltage (LV) or medium voltage (MV) networks, and for this reason they do not influence directly the EHV/HV system. In fact, the particular daily pattern of PV production mainly affects the load demand, by contributing to increase in Sardinia the excess of thermal power production during the peak hours of the day. Furthermore, an additional load demand reduction is to be expected with the integration of mini/micro CHP, if natural gas will be available at reasonable cost. Indeed, Sardinia is the only Italian Region that is not supplied by the Italian Natural Gas Network, but a new infrastructure is going to be contracted to deliver Algerian natural gas to Sardinia, Tuscany and Italy, by the end of 2015. Finally, PV and CHP have been modeled with a demand reduction considering social habits, solar availability and weather conditions.

POWER GENERATION AND LOAD DEMAND SCENARIOS AT 2020 AND 2030

GRID EXPANSION

Periodically TSO elaborates grid development plans based on forecasts and trends of electrical energy demand needs to grid upgrade and requests for integrating new power plants [4]. The power grid upgrade investments that will be concluded in 2020 are shown in Fig. 3. From 2011, the bipolar ±500 kV 1000 MW HVDC submarine cable connection between Sardinia and the Italian mainland

(SA.PE.I.) is put into service. For the 2030 scenario some reasonable hypotheses for the development of Sardinian grid are assumed. Firstly, it has been supposed that the old HVDC connection to the mainland (SA.CO.I) is put back into service with the same capacity of the existing one (300 MW). Also upgrades of the existing 150 kV low capacity lines in the north-west of Sardinia are hypothesised. Moreover, a new monopolar 500 MW 500 kV HVDC link is assumed between Algeria and Sardinia in order to export solar energy from the South to the North of the Mediterranean [6, 7].

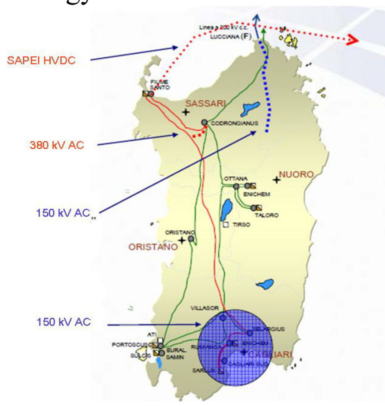

Fig. 3 - Upgrade in 2020 power grid

LOAD FORECAST

The 2020 and 2030 expansion scenario is based on two different expected load growth rates based on TSO's predictions [8, 9]. Table 1 reports the load demand forecast and relative growth rates for 2030 and 2020 scenarios with the 2008 registered values.

Tab. 1 - Annual load demand and growth rates for 2020 and 2030 scenarios

	2008	2020		2030	
Scenarios	**Pload [MW]**	**Growth rate per year (%)**	**Pload [MW]**	**Growth rate per year (%)**	**Pload [MW]**
Summer peak load	1825	1,5	2182	1	2410
Winter valley load	1020	0,9	1136	1	1255

The PV generators produce during the daylights and they cannot reduce the maximum peak load, that is registered in Sardinia from 18:00h to 22:00h. Anyway, the demand profile shows also a second peak load period from 11:00h to 14:00h, slightly lower than the maximum in the evening. Then, the PV production can reduce the overall yearly power losses and, potentially, the number of possible congestions caused by excessive demand (Fig. 4). Consequently, the projection for the summer peak load scenario (Tab. 1), remains unchanged.

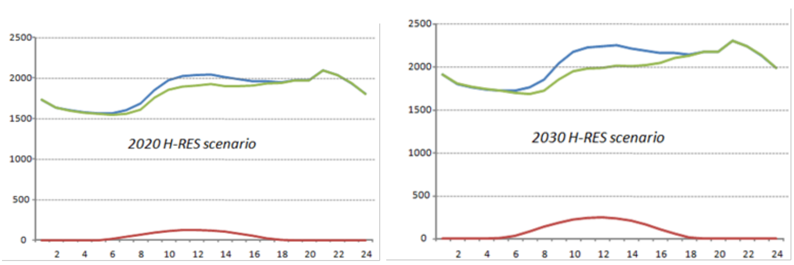

Fig. 4 - PV generation effect on the summer peak demand profiles for 2020 and 2030

Also micro-CHP natural gas fueled have been considered. CHP may be assumed to be available 24 hours per day, even though it generally follows the heat demand that reduces at night. It is then reasonable to assume that micro-CHP will provide a further energy demand reduction, but such reduction will be different at peak and off-peak hours.

GENERATION EXPANSION

Table 2 shows the foreseen power capacity in 2020 and 2030, as well as the contribution from RES. It could be noticed that hydro generation will not increase.

The only predictable investments on thermal generation infrastructures will be focused on the efficiency improvement of the existing generation plants. Other investments are to be expected if the proposed natural gas pipeline from Algeria will be realized. In order to make more critical the 2030 scenario, it has been also supposed that one unit of the conventional thermal power plants will be put out of service, increasing the ratio between RES and thermal generation. The solar thermodynamic with concentrating solar plants (CSP) is supposed to be exploited, in 2020 with the connection of one 20 MW CSP, and in 2030 by the integration of larger CSP plants. In addition micro-CHP has been also simulated.

Tab. 2 - Expected generation capacity in Sardinia [MW]

Generation Technology	**Voltage Level**	**2030**	**2020**	**2008**
Hydro	EHV/HV	466.2	466.2	466.2
Thermal	EHV	3 158.0	3 358.0	3 268.0
Wind	EHV/HV/MV	1 500.0	1 000.0	453.3
Photovoltaic	MV/LV	400.0	200.0	15.5
CHP	MV/LV	200	70	0.0
Solar thermodynamic CSP	HV/MV	80.0	20.0	0.0
Biomass + Urban Residual	MV	140.0	100.0	15.8
Total		**5 944.2**	**5 214.2**	**4218.8**

METHODOLOGY

In order to characterize the steady-state operation of the Sardinian electricity system, AC power flow studies using a Newton-Raphson iterative method were performed for each presented scenario. The Sardinian transmission grid has been implemented in a commercial simulation tool (PSS®E by Siemens), by using the official data published by the Italian TSO (*TERNA*) and assuming some hypotheses, also taking into account that not all of Sardinian power system data are public.

In the study, RES production is dispatched with the highest priority, being the RES curtailment an extreme action to be taken only when severe network contingencies occur or for thermal generation constraints. As a consequence, the dispatching of the thermal generation units is scaled down in accordance with their technical constraints (e.g. minimum power production).

In the 2030 scenario, the inflow of 500 MW from the CSP in Algeria through the supposed HVDC link has been considered, intended to the central of Europe through the SA.PE.I. HVDC link. In this case, the power flow studies have been carried for both the following cases:

1. The CSP power has always higher dispatch priority versus Sardinian wind production. In this case the export capacity of the Sardinian grid is practically halved (the available SA.PE.I. HVDC link capacity changes from 1000 to 500 MW).
2. The Sardinian wind production has higher dispatch priority versus the Algerian power import. In this case, it has been assumed that the import from the Algerian CSP power plants could be curtailed in order to allow full wind production.

Security of power system requires the availability of an adequate amount of active power that can be controlled (increased/reduced) promptly, in case of a sudden unbalance between generation/demand. The reserve is equal to the biggest thermal – gas fired – power plant (500 MW, roughly).

RESULTS

In 2020 the 1000 MW HVDC SA.PE.I connection overcomes the capacity limits of the SA.CO.I., and permits an unconstrained export of the wind power production in every scenario, including the less favourable conditions characterized by High RES penetration and valley load. The AC power flow studies have been carried out assuming extreme wind availability, which pushes the wind production to achieve the 90% of its installed capacity. Furthermore, one concentrating solar power plant (20 MW) has been considered connected directly to the 150 kV *Ottana* substation. Finally, the connection of micro-CHP (70 MW) to the MV/LV network has been simulated.

At peak hours, due to the location of the windiest areas, wind farms and seasonal touristic load in the North-east of Sardinia, the 150 kV transmission network will experience some severe contingencies

that might limit the power flow to Corsica, currently supplied with an MV submarine cable from Sardinia. Different cases have been studied to simulate the influence of energy demand in Corsica.
Tab. 3 shows the active power, load demand (export included) and energy losses (transformer iron losses included) obtained in some scenarios characterized by different percentage of wind generation (with reference to its installed capacity) and exploitation of Corsica connection (SAR.CO.).

Tab. 3 - Simulated scenarios' key values for 2020

	CASE STUDIES	Generation [MW]	Active Load [MW]	Active Losses [MW]
1	Peak Load-Wind 50%- SAR.CO. 50%-NO PV	2 725.1	2 693.4	31.7
2	Peak Load-Wind 90%- SAR.CO. 50%-NO PV	3 134.8	3 100.6	34.2
3	Peak Load-Wind 90%- SAR.CO. 100%-NO PV	3 135.7	3 100.7	35.2
4	Peak Load-Wind 90%- SAR.CO. 100%-PV	3 075.4	3 040.8	35.2
5	Peak Load-Wind 90%- SAR.CO. 100%-PV and CHP	3 004.0	2 970.2	34.8
6	Valley Load-Wind 50%- SAR.CO. 100%-NO PV	1 852.8	1 832.0	20.8
7	Valley Load-Wind 90%- SAR.CO. 100%-NO PV	1 852.8	1 832.0	20.8
8	Valley Load-Wind 89%- SAR.CO. 100%-NO PV and CHP	2 273.4	2 248.8	24.6

The scenarios with the greatest losses have the SAR.CO. exploited up to 100% and 90% of wind generation, without the load reduction given by the PV generation; the smallest losses are concentrated in the valley load scenarios in the same conditions. It is worth to notice that the lower is the RES penetration in the system, the higher the value of the losses. The increased power production causes a greater exploitation of the 380 kV network and HVDC connections. Consequently, the 150 and 220 kV network is less used with a reduction of power flows on those lines that are characterized by higher resistance. Globally, the combination of the two effects leads to an energy loss reduction and could be considered a benefit of the high share of RES in the system. Also the usage of existing transmission assets benefit from RES integration. The number of congested branches is reduced, because the power flows mainly through the 380 kV trunk branches with greater margins of exploitation (Fig. 5). It is also worth to noticing that micro-CHP may have the capability to improve the system with a significant reduction of the number of congested branches even though there are some lines exploited up to 90% or 100% of the rated capacity (scenarios with high export).

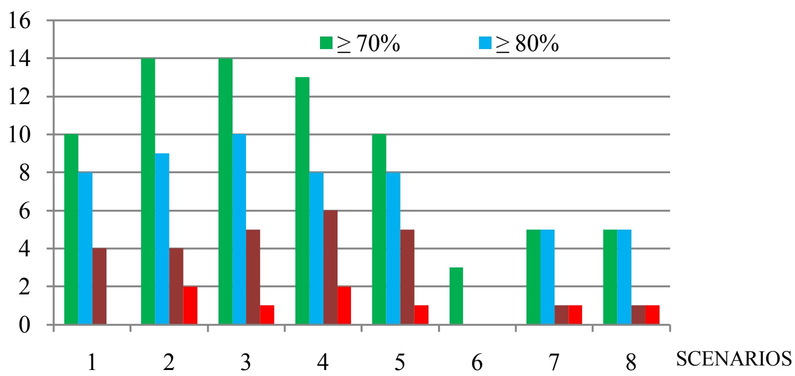

Fig. 5 - Number of branches within each congestion level in 2020 scenarios.

In 2030 the main novelty for the Sardinian grid is the 500 MW HVDC link which will connect Algeria to Sardinia to export the African CSP generation towards Europe. Depending on the assumed dispatching priority, the SA.PE.I. HVDC link capacity available to export the Sardinian RES power generation will be reduced, causing in some cases RES generation curtailment. The SA.CO.I. revamping has been considered to increase the export capacity to the mainland.
Table 4 shows with dispatch priority for the power from Algeria and different usages of the Algerian CSP the active power generated, the load demand (export included), and the energy losses (transformer iron losses included).

Tab. 4- Simulated scenarios' key values for 2030

	CASE STUDIES	Generation [MW]	Active Load [MW]	Active Losses [MW]
1	**Peak Load-Wind 90%- SAR.CO.0%-NO PV-Algeria 100%**	3 669.4	3 625.0	44.4
2	**Peak Load-Wind 90%- SAR.CO.0%-PV-Algeria 47%**	3 397.2	3 357.1	40.1
3	**Peak Load-Wind 90%- SAR.CO.0%- PV-CHP-Algeria 6.5%**	3 194.1	3 157.1	36.8
4	**Peak Load-Wind 90%- SAR.CO.100%-Algeria 60%**	2 715.2	2 682.5	32.7
5	**Peak Load-Wind 90%- SAR.CO.100%-CHP-Algeria 40%**	2 601.6	2 569.7	31.9

The scenario that has the largest loss contribution is the one with the maximum wind generation and the utmost import from Algeria. In this scenario, energy demand is the highest and the transmission system is heavily exploited. Nevertheless, the balance between the power locally produced and the local consumption allows not exceeding the rated capacity of the lines (Fig. 6).

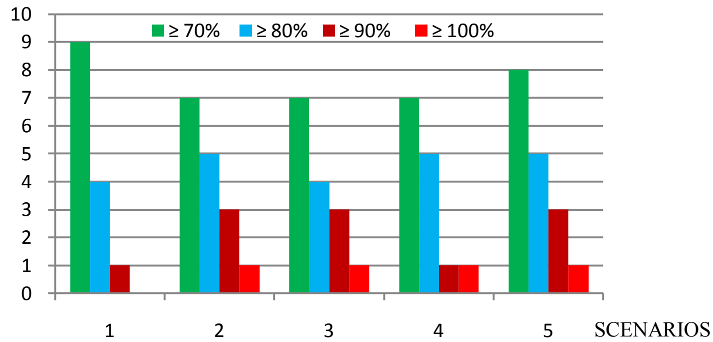

Fig. 6 - Number of branches within each congestion level in 2030 scenarios

The introduction of the PV and micro-CHP leads to the reduction of total active power losses and this benefit is followed by a decrease in the exploitation of the lines. The foreseen upgrade of the network at 2030 will allow reducing many of the congestions expected in the year 2020. However, in order to accept the electricity from Algeria, new investments should be planned to upgrade and reinforce both 220 kV and 380 kV systems, which will be committed to transport large quantities of energy through Sardinia to feed with green energy the mainland and other European countries.

CONCLUSIONS

The integration of moderate quantities of RES can be quite beneficial for system operation, leading to loss reduction and improvements in the voltage profiles of the network. However, in scenarios where large RES generation facilities are built, namely far from the main urban consumption areas, long distance power transmission infrastructures are required, an increase in active losses takes place and some additional difficulties in local voltage control may also arise.

Large scale integration of RES into the electric power system is possible if reinforcements of the transmission infrastructure are performed in due time, anticipating the installation of the new generation facilities in specific geographical areas where the RES is available.

By analysing the results, it is possible to summarize the following conclusions.

1. *Year 2020*. The TSO planned upgrades of the Sardinian grid allow tolerating most of the possible generation configurations that can be reasonably imagined for this time horizon. In particular:
    a. The SA.PE.I HVDC link to mainland raises the export capacity of the Sardinian system and permits increasing significantly the generation level of the conventional thermoelectric technology, limited only by reserve margin issues and by the existing turbine limits (57% of the nominal installed capacity in *high RES* penetration scenario against the 43.5% currently assessed).
    b. The wind production takes advantage from the enlarged export capacity, and no curtailment is required. However, some limitations may occur with high wind production due to local network congestions. Specifically, some bottlenecks exist for transfer large amount of wind power from the HV system to the EHV system.

c. The PV generation does not reduce the evening peak load of the Sardinian system, but is able to partially reduce the active losses and the exploitation of some 150 kV lines, especially during the midday peak load.
d. Finally, from the point of view of the Italian electricity market, the almost complete elimination of the congestions on the Sardinia – mainland connection allows reducing the zonal prices of Sardinia as well as the unique national energy price.

2. *Year 2030*. The Sardinian grid Steady-State behavior is strongly influenced by the presence of the additional HVDC link from Algeria, preferential route for the export of the "green" power produced with the foreseen North-African CSP plants towards Europe. This new configuration of the Sardinian system reduces the available export capacity to the mainland, partially compensated by the revamping of the SA.CO.I. HVDC link. This partial reduction can affect the generation levels of the Sardinian power plants. In particular:
   a. In order not to curtail the wind production during the evening peak load, it is necessary to limit the maximum generation level of the conventional thermoelectric power plants (around 50% of the nominal installed capacity).
   b. At evening peak load RES and wind farms in particular, do not suffer any generation curtailment for power from Algeria. During midday with maximum PV generation, RES generation might be necessary to preserve adequate reserve margin and comply with technical constraints of thermal generation. The use of storage and the integration of electric vehicles should be investigated to reduce the need of curtailment.
   c. At off-peak hours, the wind production has to be limited to no more than 80% of its nominal capacity if Algerian power gets dispatch priority. On the contrary, if the Sardinian RES generation gets highest dispatch priority, the HVDC connection with Algeria will be used at 60% of its capacity.

The research carried out showed that HVDC link from North Africa to Sardinia should be limited to 500 MW mainly for two reasons. The first reason is the high wind power production in the island associated to a dramatic reduction of power demand accrued by the industrial and economic crisis. The second reason is the Sardinia 380 kV backbone that is not capable to deliver the excess of power from Algeria from south to north. The SA.CO.I revamping to reach a 500-600 MW of power capacity might be useful to cope a transit of 1000 MW from Algeria but in that case huge network reinforcements are necessary (e.g., doubling the 380 kV Sardinian backbone).
Finally, it has been demonstrated with the study that the 150 kV network is the most critical asset of the Sardinia transmission grid where the majority of wind farms are connected particularly in the north-east part of the island. Connecting the wind farms to higher voltage systems such as 220 kV or 380 kV networks can alleviate network congestions, but at very high costs for power producers and system stakeholders. A long term solution is represented by a large scale deployment of electric vehicles that will increase the demand of electricity, and will introduce a high level of flexibility in the energy. Electric to grid vehicles and storage devices will be also necessary to minimize the burden on the distribution system caused by PV and, hopefully, by CHP.

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