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A European supergrid for renewable energy: local impacts and far-reaching challenges

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ABSTRACT

This article assesses the impact of extensive deployment of indigenous and external renewable energy sources on a local electricity system (Sardinia Island) and discusses the main challenges faced by the European power grids in integrating high shares of renewable-based generation technologies. It presents the 2030 scenarios for the Sardinian power system and the results of steady-state analyses in extreme (renewable) generation and consumption conditions. These results are eventually combined with the assessment of key technology development trends to explain how this can affect the development of a European supergrid. In general, the article stresses that rendering the bulk-power system capable of accommodating high renewable energy penetration not only requires reinforcing the electricity highways but also demands carefully planning the architecture of and the interface with regional power systems.

1. Introduction

EU energy policy goals, as well as the Europe 2020 economic targets, will not be achievable without a major shift in the way European infrastructure is developed. According to An Energy Policy for Europe (European Commission, 2007b) technological improvements, greater efficiencies, resilience to a changing climate and new flexibility will be necessary. Adequate, integrated and reliable energy networks are a crucial prerequisite not only for EU energy policy goals, but also for the EU's economic strategy (European Commission, 2010). Developing our energy infrastructure will not only enable the EU internal energy market to function properly, it will also enhance security of supply, allow the integration of renewable energy sources (RES), increase energy efficiency and enable consumers to benefit from new technologies and intelligent energy use (European Commission, 2010).

On one hand, the evolution of European low and medium voltage (LV, MV) distribution grids is expected to be predominantly steered by the increasingly swift diffusion of distributed energy resources (DER), defined as small-sized power demand and supply-side devices, such as distributed generation (DG) (RES-based units, fuel cells and cogeneration of heat and power units) and storage/conversion technologies (including electric vehicles). The drive for DER penetration will push the evolution of the distribution network towards smart grid concepts. A smart grid is an electricity grid that allows extensive integration of DER and uses advanced information and communication technologies (ICT) to deliver electricity more cost-effectively, more sustainably and in response to consumer needs (SETIS, 2011).

On the other hand, the deployment of RES in large-sized units (typically above a few hundred MW) will impact on the evolution of the higher voltage (HV) electricity transmission network towards a supergrid concept. A supergrid can be defined as an electricity transmission system, most likely based on direct current technologies, designed to transport over very long-distances large-scale power from remote areas to consumption centres (FOSG, 2010). A supergrid could well be a subsystem embedded in a traditional transmission grid, i.e. a high transfer capacity layer superimposed on the traditional transmission system.

It has to be stressed that the correlation between transmission-super and distribution-smart grids is only approximated and certainly loose. Some reasons for this are: the border between transmission and distribution systems cannot always be clearly identified and will dynamically change; transmission will also

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become smarter (even if the transmission grid is already partially smart), since further intelligence is needed to better interact with completely redesigned distribution systems and to more effectively balance intermittent renewables.

The aim of this article is to improve current knowledge of the influence of extensive penetration of RES generators in an electricity system. This is achieved by studying the evolution of the electricity system in the island of Sardinia, Italy. Sardinia is a suitable case study as it has a relatively confined electricity grid with limited interconnections to the mainland, has relatively high solar and wind power potential, and offers viable options for further interconnections between Europe and North Africa. The analysis of the electricity grid is based on steady-state modelling for the year 2030. The 2008 grid conditions are taken as reference.

Two generation scenarios are considered for the case study: business-as-usual and high RES penetration. Based on demand profile forecasts, the models involve the planning of generation units and network infrastructures.

The steady-state analysis of the Sardinian grid has been carried out by means of alternating current (AC) power flow studies applied to the anticipated load and generation scenarios, as described in Section 2 of the article. The 2030 grid expansion and results of this analysis indicate possible congestion of the grid, distinguishing the critical events caused by the presence of RES generators (typically wind farms) from those primarily originated by the peak load. Section 3 combines the power flow analysis results with general findings on RES and future grid compatibility to explain how the European supergrid concept can be affected and which local impacts and cross-border challenges shall be addressed. The longer term scenario presented is based on the argument from A European Strategic Energy Technology Plan (European Commission, 2007a) that, by that time, the energy system will mostly rely on technologies currently mature or still under development. The final section of the article sets out the overall conclusions of the analysis.

2. Case studies for Sardinia in 2030

2.1. Situation of the electricity system in 2008

2.1.1. Generation and load

The Sardinian electricity system in 2008 is taken as reference. The consumption of electricity in Sardinia that year reached 11 935 GWh (excluding power transmission losses, auxiliary power plant consumption, hydro pumping and exchanges through the interconnectors with the mainland), which corresponds to an average electricity demand of 7154 kWh per person, an increase of 12% on 1998.

Fig. 1 shows four representative load curves observed in 2008, each one associated with a given season. The highest peak load has a tendency to appear around 8–9 p.m. in summer (summer peak), and the lowest trough load at night at around 3–4 a.m. in winter (winter trough). Maximum summer peak and minimum winter trough load data are thus chosen for this study in order to create challenging conditions for grid operation with high renewable energy shares.

In 2008, Sardinia's total generation capacity was 4218.8 MW (see Table 1), which corresponds to 4.1% of Italy's total generation capacity. Energy production in Sardinia is dominated by coal- and oil-fired thermal plants that account for more than 90% of total electricity generation. Other energy sources include hydropower, with 4.5%, and biomass and urban waste, with 1.5% of total electricity generation in 2008. Despite the local favourable conditions for energy production from the wind and the sun (photovoltaic (PV) only), a very small share of electricity is generated from these resources, 4.3% and 0.1% respectively. Due to the orography and hydrography of the Sardinian territory, hydro generation capacity is very limited and the potential is considered almost entirely exploited. The maximum load value in 2008 appears in summer and is 1825 MW.

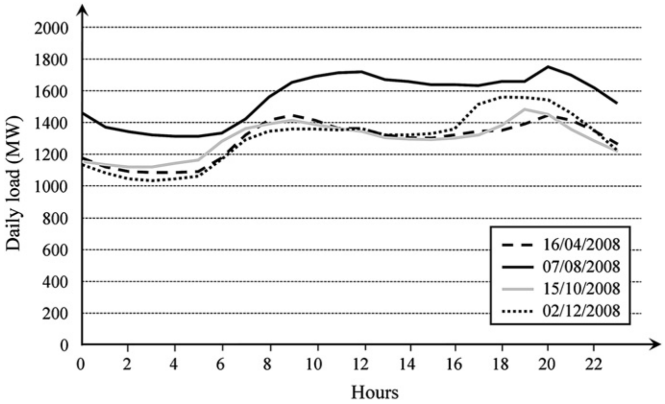

Fig. 1. Seasonal daily load diagrams for the Sardinian electrical system.

2.1.2. Electricity grid

The analysis of Sardinia's electricity grid in 2008 (Fig. 2) by TERNA, the Italian Transmission System Operator (TSO), highlights main bottlenecks and weaknesses:

- 150 kV grid in the north-east and 220 kV lines in south region are weakly meshed. This leads to line overloads and voltage problems in these regions especially in the summer when there is a significant increase in demand.
- The existing high voltage direct current (HVDC) link to the mainland through Corsica (SA.CO.I.) is very old and therefore has limited export capacity (one part of this link is the SAR.CO Sardinia-Corsica connection).
- The weakness of the transmission and distribution grid in some circumstances does not allow the SAR.CO connection between Sardinia and Corsica to be fully exploited.
- In the southern part of Sardinia (Cagliari area) there is a need for improved reliability and continuity of service, in particular close to the Sarlux thermal power plant, mainly because of congestion in the transmission grid.

The projects planned by the TSO to overcome these critical situations will lead to the elimination of grid bottlenecks, by reinforcing the grid, increasing the use of new generation capacity from RES and improving the connections to the mainland. The main reinforcements, as described by the TSO (TERNA, 2009), have been implemented in the network model base case considered for the analyses.

Furthermore, Sardinia's grid in 2008 characterises with specific main network distinctiveness what is the only 380 kV line, which

Table 1
Sardinian generation capacity and maximum load in 2008.

	Network level	
Maximum load, MW		1825.0
Generation capacity, MW		4218.8
Including		
Hydro	EHV/HV	466.2
Thermal	EHV	3268.0
Wind	EHV/HV/MV	453.3
PV	MV/LV	15.5
Biomass + Urban Waste	MV	15.8

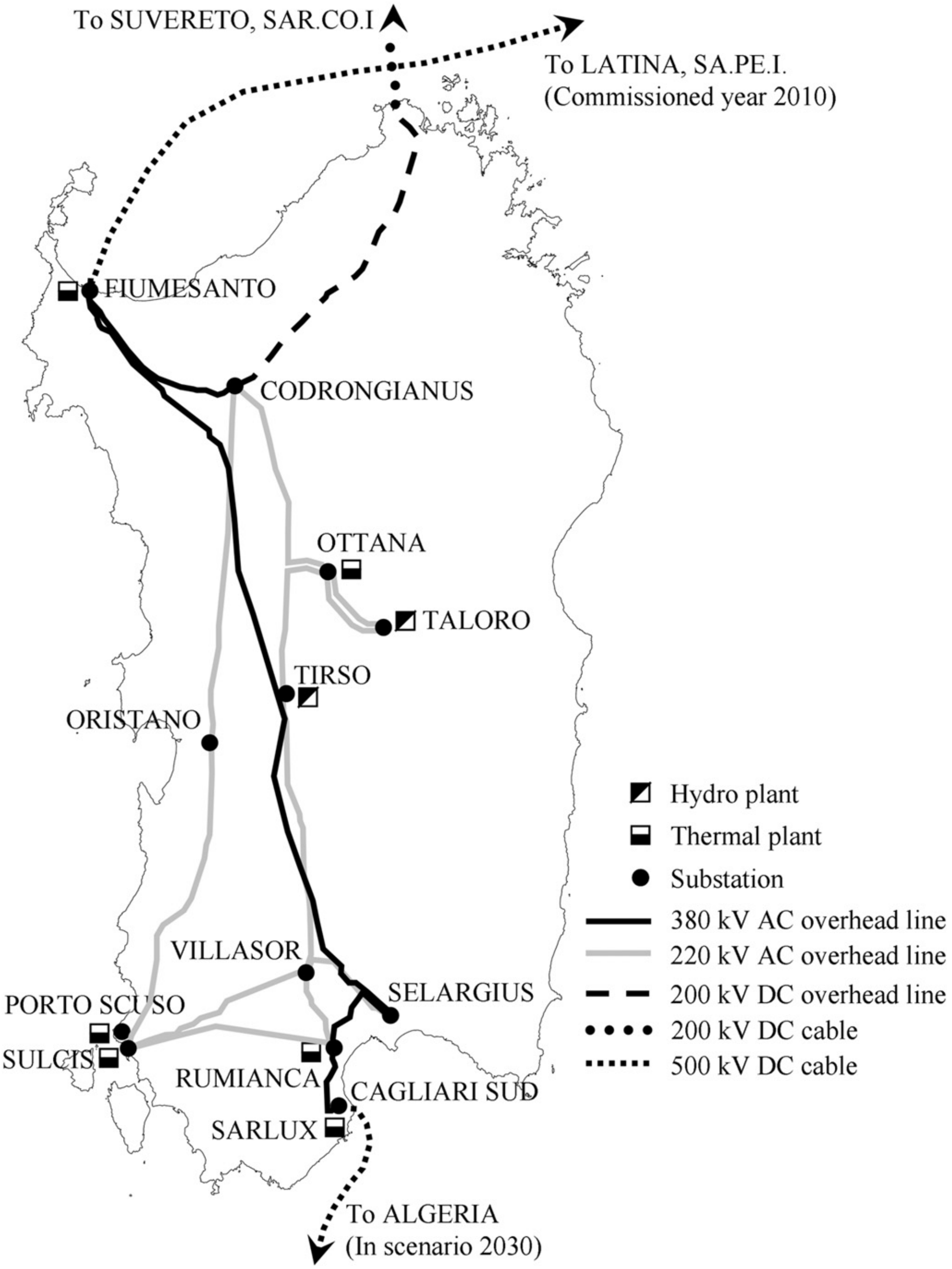

Fig. 2. A schematic view of the Sardinian transmission grid.

crosses the island from the south to the north-west, is not meshed and is not heavily loaded under the energy system conditions prevailing in 2008.

2.1.3. *Summer peak load flow in windy weather*

Initially, summer peak load studies for the year 2008 were performed, in order to characterise the current steady-state operation of the Sardinian electricity system and constitute a reference point for the studies in the future scenarios. A capacity of 300 MW was considered for the existing SA.CO.I. HVDC link.

The power flows for summer peak load in 2008 are summarised in Table 2. The conventional generation technologies considered are thermoelectric and hydroelectric with dam. The generation limit of the Sardinian power plants based on hydroelectric technology

Table 2
System summary for average summer peak load in 2008 (wind power 90% of rated capacity).

	Active (MW)	Reactive (MVar)
Generation	2128.6	1323.7
From hydro	305.9	
From thermal	1428.2	
From wind	394.5	
Imports	0.0	0.0
Load	1805.4	873.8
Exports	298.8	0.0
System losses	24.4	449.9

roughly corresponds to 85% of their nominal installed capacity (466.2 MW, see Table 1). The dispatching hypotheses for thermoelectric technology in the power flow studies highlighted an overall generation limit corresponding to approximately half of the nominal thermoelectric capacity installed in Sardinia (including gas turbines mainly used to meet peak power demand). Furthermore, due to their relatively low contribution, photovoltaic (PV), biomass and urban waste power outputs were disregarded in the 2008 scenario.

In 2008 wind farms were concentrated in the north-west and south-east of Sardinia. In this scenario an important contribution to compensation of the wind power surplus is made by the HVDC link, which exports it to the mainland.

Total active and reactive losses in the Sardinian electricity system are 24.4 MW and 449.9 MVar respectively at peak demand and at a wind power factor of around 90%. It should be noted that these system losses only refer to the Sardinian AC system (active losses in the HVDC cables are not included).

2.2. *Scenarios for generation and load in 2030*

The 2030 scenarios are based on two different expected generation capacity cases: business-as-usual and high penetration of RES. For the load, an annual growth rate of 1.5% is assumed for the summer peak from 2008 until 2020 and an annual growth rate of 1% from 2020 to 2030, as proposed in the study by Centro Elettrotecnico Sperimentale Italiano (CESI, 2005). As a result, the summer peak load in Sardinia grows from 1825 MW in 2008 to 2182 MW in 2020 and 2410 MW in 2030 (see Table 3). For the winter trough a smaller annual growth rate of 0.9% from 2008 to 2020 and 1% from 2020 to 2030 is assumed following the same study. This results in a predicted load demand of 1020 MW in 2008, 1136 MW in 2020 and 1255 MW in 2030.

It is further assumed that traditional fossil-fuel based generation capacity will remain constant for the next 10–20 years. The only investment in traditional generation infrastructure that has been considered is improvement of the efficiency of the existing generation plants.

Concerning RES generation, the business-as-usual scenario is based on the TSO's current predictions (TERNA, 2008). The high RES penetration scenario is based on additional investment in wind and solar power. This causes a significant increase in RES capacity compared to the business-as-usual scenario. For both scenarios concentrated solar power (CSP) is considered, because this technology is predicted to offer huge potential in the Mediterranean area according to the German Aerospace Centre (2006).

The expected generation capacities for the business-as-usual scenario and the scenario with high penetration of RES are summarised in Table 3. The grid is divided into LV (≤1 kV), MV (≤30 kV, 15 kV in Sardinia), HV (150 kV), and extra HV (220 and 380 kV).

Table 3
Sardinian expected generation capacity and load in 2030 for business-as-usual and high RES scenarios.

	Network level	Business-as-usual (MW)	High RES (MW)
Maximum load		2410.0	2410.0
Minimum load		1255.0	1255.0
Generation capacity		4844.2	5604.2
Including			
Hydro	EHV/HV	466.2	466.2
Thermal	EHV	3158.0	3158.0
Wind	EHV/HV/MV	1000.0	1500.0
PV	MV/LV	200.0	400.0
CSP	HV/MV	20.0	80.0

In the high RES penetration scenario wind power was assumed to reach a capacity close to Sardinia's maximum wind potential, which according to the National Association for Wind Energy (ANEV, 2008) is 1750 MW. In the business-as-usual scenario a more prudent estimation was adopted, taking into account the existence of several environmental constraints affecting Sardinian territory. The other renewable energy technologies (e.g. PV and CSP) will continue their development trend. It is expected that biomass and urban waste generation capacity will increase in future, but in the 2030 scenarios generation from these technologies is assumed to be zero. This decision is mainly based on curtailment of flexible generators such as biomass and urban waste at high wind speed. Furthermore, in all 2030 scenarios the power factor of Sardinian CSP is assumed to be around 0.5.

The new wind farms in the business-as-usual scenario are spread across the whole of Sardinia with a higher concentration on the western coast, but in the high RES scenario additional wind farms are installed in the north. The only CSP plant in the business-as-usual scenario is connected to the Ottana substation in the middle of Sardinia and new CSP plants are spread evenly along the western side in the high RES scenario. New PV generators are distributed evenly over the whole island in both 2030 scenarios.

In order to make the scenarios more critical, it was also assumed that one conventional thermal power plant (200 MW) will be decommissioned, increasing the share of RES.

2.3. *Grid expansion for 2030*

TERNA periodically draws up grid development plans until 2020 based on forecasts and trends in electricity demand, grid upgrading needs and requests for integrating new power plants (TERNA, 2009). These plans were taken into account in the future grid development scenarios discussed in this article.

The most important investment considered fully operational by the end of 2010 is the bipolar ±500 kV 1000 MW HVDC submarine cable connection between Sardinia and the Italian mainland (SA.PE.I.). This investment is driven by the limited capacity and the ageing issues of the existing HVDC link (SA.CO.I., 300 MW). The SA.PE.I. boosts the security of the electricity system in Sardinia and the capacity to export thermoelectric and RES power production to the mainland (TERNA, 2009).

The further (from 2020 to 2030) network investments that the TSO will implement in the Sardinian transmission grid have not yet been published by TERNA. However, some reasonable hypotheses are made in this article for the development of the Sardinian grid based on earlier TSO trends.

First of all, as mentioned in the previous sections, it has been assumed that the old HVDC connection to the mainland (SA.CO.I) is put back into service with the same transmission capacity (300 MW).

Some upgrades of existing lines in the Gallura region (north-west) are included in the grid development for the Sardinian system for 2030, specifically all the 150 kV lines with relatively low capacity.

A new HVDC link is also assumed between Algeria and Sardinia. In past years some feasibility studies have been carried out on HVDC interconnection projects with a view to exporting solar energy from the south to the north of the Mediterranean (German Aerospace Centre, 2006). In particular, regarding the Algeria-Italy HVDC interconnection, a feasibility study by Cova et al. (2005) identified two solutions. In the first solution between El Hadjar and Latina the cable is planned to be placed in the sea close to the east coast of Sardinia, but the sea depth of around 2000 m could challenge its technical feasibility. In the second solution the cable from El Hadjar is connected directly to the 380 kV backbone of Sardinia (see Fig. 2).

For the purposes of this paper, only the second option has been considered. The connection power rating would be approximately 500 MW at 500 kV in monopolar configuration. In addition, exporting 500 MW from Algeria to the Italian mainland through Sardinia does not require any reinforcement of the south-north 380 kV transmission backbone in Sardinia (at grid conditions in 2008).

2.4. General methodology

In order to characterise the steady-state operation of the Sardinian electricity system, AC power flow studies were conducted for each of the scenarios presented in Subsection 2.2. These studies were performed using a Newton–Raphson iterative method based on a power flow computational tool. The biggest Sardinian coal power plant, Fiumesanto, was chosen as a slack node.

A number of hypotheses were adopted in order to perform the power flow studies, also taking into account the fact that not all the data on the Sardinian power system are public.

First of all, RES production is assumed to be dispatched with the highest priority. These plants can be curtailed only in the event of specific network contingencies or for minimum generation requirements. As a consequence, dispatching of the conventional generation technologies is scaled down in accordance with their technical constraints. The minimum power production for thermo- and hydroelectric technologies is assumed to be around 50 and 85% of their rated power respectively.

In 2030 a new energy import is considered, corresponding to 500 MW CSP production from Algeria through the assumed new HVDC link and destined for central Europe. Two possible situations were considered for the power flow studies.

1. CSP always has higher dispatch priority versus Sardinian wind production. In this case the export capacity of the Sardinian RES generators is practically halved, causing possible curtailment of local RES production.
2. Sardinian wind production has higher dispatch priority versus the Algerian power imports. In this case, it is assumed that imports from the Algerian CSP plants could be curtailed in order to allow full wind power production in Sardinia.

Security of the electricity system requires the availability of an adequate amount of active power that can be controlled (increased/reduced) promptly in the event of a sudden imbalance between generation and demand. Some of these limits are common across the whole Italian territory, and others are specific to particular regions. An amount of generation reserve at least equal to the whole production of the Sarlux plant (a little more than 500 MW) has been assumed.

Furthermore, in order to analyse the most critical situation, the power factor of wind farms is assumed to be 90%. In addition, to analyse the effects of PV power production, in the high RES scenario the midday peak load, during which PV generation is at the maximum, is assumed to equal the evening peak load, and for this reason both situations (with and without PV effect) were investigated. Losses in the HVDC links are not included in the results presented.

2.5. Results for 2030 scenarios

2.5.1. Summer peak load scenario 1: business-as-usual, windy and sunny, with priority to imports

The simulations conducted for the business-as-usual summer peak load scenario in a windy case provided active power balances listed in Table 4. Since summer peak load appears at around 8–9 in the evening (see Fig. 1), in the case with PV generation the power factor of PV plants was assumed to be decreased to 70%, which is equal to 140 MW following the data in Table 3.

Table 4
Power balances for summer peak load, business-as-usual 2030 (wind 90%, with priority to CSP imports).

	Active power balance (MW)	
	With PV	Without PV
Generation	3040.0	3040.0
From hydro	331.6	331.6
From thermal	1621.4	1761.4
From wind	937.5	937.5
From PV	140.0	0.0
From CSP	9.5	9.5
Imports	474.6	474.6
Load	2218.1	2357.3
Exports	1117.3	1117.3
System losses	40.2	40.0

Considering the energy imports from Algeria through the HVDC interconnection, the capacity of the new HVDC link is limited to 500 MW (474.6 MW due to the 23.4 MW DC line active power losses).

There is load dissimilarity in both cases 'with PV' and 'without PV' (and also in other scenarios) mainly due to the DG, what characterises with electricity generation and consumption in distribution grids. In such a way electricity can be consumed in the place where it is generated, consequently the request for power from the distribution substation decreases in that time. In addition, different load and generation configurations and values in the grid cause differences in load flow results.

2.5.2. Summer peak load scenario 2: high RES, windy and cloudy, with priority to imports

An AC power flow analysis for the high RES penetration scenario for the summer peak load (disregarding PV generation) was also carried out (see Table 5).

In this scenario too the 500 MW CSP flow imported from Algeria was given dispatching priority versus Sardinian RES generation. Despite this limitation, the RES power plants do not suffer any generation curtailment, since the SA.CO.I. and SA.PE.I. HVDC link capacities are still sufficient to accommodate all the power generation, as can be seen from the 'Exports' row in Table 5. However, if PV production is included (equal to the midday peak) it would be necessary to curtail some Sardinian RES generation, in order to preserve an adequate reserve margin.

2.5.3. Summer peak load scenario 3: high RES, windy and sunny, without priority to imports

In order to properly evaluate the effect of PV generation, what is assumed to be 70% from rated capacity in summer peak load evening hours, it is considered for CSP imports from Algeria to be not prioritised. Considering the PV effect causes the HVDC links to the Italian mainland to be fully exploited and requires the imports

Table 5
Power flow balances for summer peak load, high RES 2030 (wind 90%, without PV, with priority to CSP imports).

	Active (MW)	Reactive (MVar)
Generation	3194.9	2501.0
From hydro	332.6	
From thermal	1436.2	
From wind	1388.2	
From PV	0.0	
From CSP	37.9	
Imports	474.5	0.0
Load	2357.3	1141.0
Exports	1267.7	0.0
System losses	44.4	1360.0

Table 6
Power balances for summer peak load, high RES 2030 (wind 90%, with PV, without priority to CSP imports).

	Active (MW)	Reactive (MVar)
Generation	3170.2	2221.1
From hydro	332.6	
From thermal	1131.6	
From wind	1388.1	
From PV	280.0	
From CSP	37.9	
Import	227.0	0.0
Load	2059.4	996.8
Export	1018.4	0.0
System losses	40.1	1224.3

Table 8
Power balances for winter trough load, high RES 2030 (wind 90%, with CSP imports at 60%).

	Active (MW)
Generation	2424.2
From hydro	0.0
From thermal	998.2
From wind	1388.1
From PV	0.0
From CSP	37.9
Imports	291.0
Load	1405.1
Exports	1277.0
System losses	33.1

from Algeria to be reduced. These imports correspond to 47% of the rated capacity of the Algeria-Sardinia HVDC link. The results of the analysis of this scenario are presented in Table 6.

With reduced CSP imports from Algeria the active and reactive losses in the Sardinian transmission system are reduced to 40.1 MW and 1224.3 MVar respectively if compared with losses in the case of full Algerian imports and without PV generation (44.4 MW active and 1360 MVar), as summarised in Table 5. The reduction of losses is due to the reduced use of the 380 kV lines, which should be heavily exploited to allow the north-south transmission within the island of imported CSP, and the load reduction achieved through massive penetration of PV units in DG, which mainly influences the 150 kV system.

2.5.4. Winter trough load scenario 1: business-as-usual, windy, night, with priority to imports

The simulations conducted for the business-as-usual winter trough scenario with priority to CSP imports result in the power balances listed in Table 7.

Due to its storage capability, the CSP generation imported via the HVDC link has been fully considered in such a trough load scenario, assuming that the CSP plant produces its full output also during the night-time in Sardinia. On the other hand, PV in Sardinia does not produce at night. This allows the unconstrained generation of Sardinian wind farms without excessive overloads in the system.

2.5.5. Winter trough load scenario 2: high RES, windy, night, without priority to imports

The most critical steady-state analysis carried out for the 2030 scenario is the configuration with high RES penetration in the Sardinian generation system and winter trough load, due to the huge amount of unpredictable generation and the simultaneous minimum demand (Table 8).

If dispatching priority is given to Sardinian RES generation versus the CSP production from Algeria (considering its storage capability), the maximum amount of CSP imports admitted into the Sardinian transmission system is equal to 60% of the HVDC link capacity. This allows maximum exploitation of the wind generation potential.

Table 7
Power balances for winter trough load, business-as-usual 2030 (wind 90%, with priority to CSP imports).

	Active (MW)
Generation	2254.6
From hydro	0.0
From thermal	1307.5
From wind	937.6
From PV	0.0
From CSP	9.5
Imports	475.6
Load	1405.1
Exports	1291.0
System losses	34.1

2.5.6. Conclusions for the Sardinian system

The steady-state behaviour of the Sardinian grid could be strongly influenced by the presence of an additional HVDC link from Algeria for energy transmission from North Africa to Europe. A new configuration of the Sardinian system of this nature would certainly reduce the available export capacity to the mainland, but this would be partly compensated by putting the SA.CO.I. HVDC link back into service. Such a partial reduction can affect the generation levels of the Sardinian power plants. In particular:

- In order not to curtail wind production during the evening peak load, it is necessary to limit the maximum generation level of the conventional thermoelectric power plants (to around 50% of the nominal installed capacity).
- If no PV production is considered (evening peak load), the other RES power plants, particularly wind farms, do not suffer any generation curtailment due to the presence of CSP flow from Algeria. However, at midday, when PV generation is at its maximum, it becomes necessary to curtail some Sardinian RES generation, in order to preserve an adequate reserve margin.
- Disregarding local network congestion and assuming priority in dispatching CSP production from Algeria, wind generation could achieve its maximum capacity only during the evening peak load periods (to the detriment of thermal power generation) and in the trough load conditions of the business-as-usual penetration scenarios. Instead, in the critical high RES penetration scenario and under the simultaneous trough load condition, the exploitation of wind technology has to be limited to no more than 80% of its nominal capacity. In contrast, if Sardinian RES generation has the highest dispatching priority, the maximum amount of CSP imports admitted into the Sardinian transmission system is equal to 60% of the HVDC link capacity.

In order to alleviate the competition between electricity imports from Algeria to mainland Italy and local Sardinian power generation (including wind farms), the construction of a bigger-capacity Algeria-Italy interconnection should be contemplated to reinforce the interconnections between Sardinia and mainland Italy and the north-south 380 kV backbone in Sardinia. Upgrading the SA.CO.I connection to a power transmission capacity of 600 MW and doubling the 380 kV Sardinian backbone could be the measures needed to fully integrate a 1000 MW interconnection with North Africa (German Aerospace Centre, 2006).

In the 2030 summer peak load scenarios, the presence of PV generation in Sardinia leads to improved efficiency of the Sardinian electricity grid, as shown in Fig. 3, where active losses in lines in two scenarios represented in Table 5 and Table 6 are compared

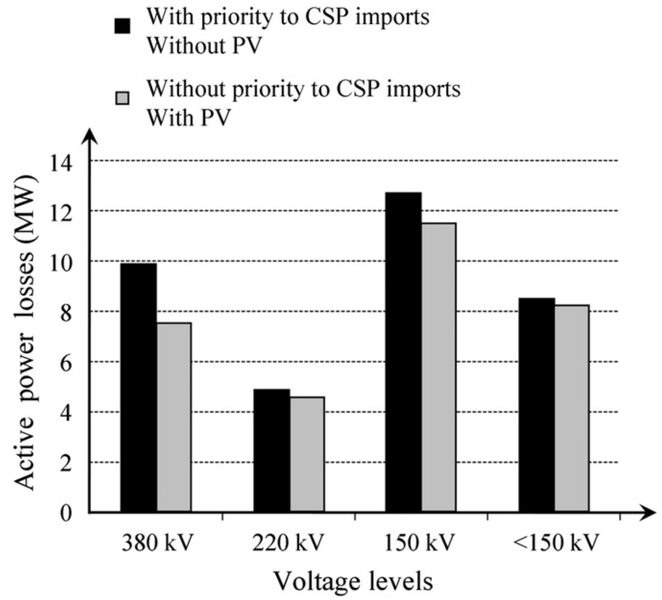

Fig. 3. Comparison of total active power losses in Sardinia's electricity grid with and without priority to CSP imports from Algeria and PV effect in high RES summer peak load scenario.

(losses in transformers are excluded). The grids with a voltage level below 150 kV include lines as from 10 kV. Furthermore, if storage technologies are eventually included and largely applied in the distribution system for shaving supply and demand peaks, congestion in the transmission system would be notably alleviated.

3. Towards a supergrid: local impacts and cross-border challenges

The above-described steady-state analysis of the Sardinian electricity grid provides general insights into the impact of high RES deployment in the electricity system, especially the adequacy of the grid to channel this increased energy production from RES, and also the rise in both import and export energy flows, where the Sardinian grid becomes part of a bulk-power transmission corridor between North Africa and Europe.

The deployment of RES in large-sized units can steer the evolution of the transmission network towards a supergrid wheeling power over long-distances from remote areas to consumption centres. It is acknowledged that a supergrid is one of the possible concepts of the future power system as the electricity networks can evolve following different and even partly competing visions. For instance, as clearly outlined by Verbong and Geels (2010) there could be three evolution pathways in the electricity system with different implications for (grid) infrastructures: further hybridisation of the infrastructure (with significant role for carbon capture and storage); emergence of a supergrid; prevalence of distributed generation and microgrids.

It is worth stressing that the aim of this section is not to offer a comprehensive socio-economic vision of the power system after 2030 but to describe key technical challenges a supergrid concept faces to further develop. This longer term scenario is based on the argument from A European Strategic Energy Technology Plan (European Commission, 2007a) that, by that time, the energy system will mostly rely on technologies currently mature or still under development.

Some general comments are worth making, stemming from the steady-state analysis of the Sardinian electricity grid.

- The integration of a moderate share of RES can be quite beneficial for system operation, due to their inherent distributed nature, leading to loss reduction and improvements in the network voltage profiles, especially when local demand-supply equilibrium is achieved in DG. This equilibrium could be reached, for example, by using flexible and decentralised power generators such as small-sized combined heat and power plants with rated power usually up to 10 MW (Andersen and Lund, 2007). However, in scenarios where both DG and remote RES generation are considered, so that long-distance power transmission infrastructures are required, an increase in active losses takes place while voltage control becomes more demanding.
- Large-scale integration of RES into the electric power system while preserving operation robustness is only possible if grid reinforcements are implemented in due time, anticipating the installation of new renewable power generation capacities in the corresponding resource areas. In order to identify these grid upgrading requirements, detailed studies should be carried out to identify the hosting capacity of network buses located near the potential geographic areas for renewable power generation, taking into account the correlation between annual variability of generation and load patterns.
- For large-scale deployment of RES in some control areas, it may happen that a surplus of renewable electricity exists, particularly during off-peak hours, leading to the curtailment of electric energy produced from these sources. In these cases, either large storage facilities are necessary, i.e. pumped hydro storage, or adequate export flows must be assured (Purvins et al., 2011). In the cases where a surplus of electrical energy from RES may occur, complementary active demand-side measures can be adopted to increase electricity consumption during trough hours. Electric vehicle dissemination would also have a favourable effect on this issue if proper management control is exercised over battery charging, such that the additional load will appear during the trough hours.

A radical change in the topology, control and operation of the electricity transmission and distribution grids is hence expected, to allow high penetration of renewable electricity and to optimise backup and storage capacities. We here argue that, from the technical point of view, in the long-run (after 2030), the European power system will not see the super/smarter transmission grid and the smart distribution grids supplanting one another. Most likely, even if power production is much more decentralised than today, both transmission and distribution systems will be needed to fulfil supplementary functions, on different geographic scales, with the key issues detailed below.

In order to harmonise the (super) transmission and (smart) distribution grids, the development and operation of the transmission–distribution interfaces will be coordinated more closely. Both transmission and distribution will be developed, not only in terms of carrying capacity but also via advanced ICT infrastructure and communication and control platforms (JRC-SETIS Work Group, 2009). Massive investments will be mobilised to keep on developing flexible, coordinated and adequate electricity networks, designed according to new architectural schemes and embedding innovative technological solutions. The development and improvement of cost-effective and coordinated high-power energy storage systems will play a vital role in facilitating greater penetration of DER by decoupling generation and energy use. Key issues to be handled relate to the remuneration of storage services for supporting renewables and avoiding grid congestion, grid access tariffs and the increasing cost of energy storage operation. Modernisation of the grids can occur with the deployment of technological options that are for the most part available, but technological breakthroughs can accelerate or even change the direction of their evolution.

After 2030, the EU system could be interconnected with the Southern Mediterranean area, through a Ring which would evolve into a trans-Mediterranean supergrid, and with the systems of Russia, Ukraine, Belarus, Moldova and the Baltic (and other) states. The Sardinian system could act as power system hub for multiterminal undersea interconnectors as it is strategically situated in the Mediterranean Sea. The European transmission system is expected to serve a fully-fledged liberalised single market and the transmission system will have to be redesigned to better operate with large yearly and seasonal variations of natural resources (especially renewable) and a possible mismatch between short-term forecast and actual renewable production.

Several projects have already started towards implementation of the above-described grid vision. One of them is the European supergrid, which involves the long-term development of an international electricity grid including the adoption of new wind (mainly offshore) and also solar power plants in and around Europe. In developing the European supergrid, it has been suggested that the approach should focus on modular development, with particular attention being paid to regional projects such as Kriegers Flak, the North Sea Offshore Grid and the Mediterranean Energy Ring (Council of European Energy Regulators, 2009). Another huge plan linked to RES integration in Europe is the Desertec concept, where most electrical power will be generated by CSP technologies (German Aerospace Centre, 2006). The planned transmission system in the Desertec concept could connect electricity generators located in the Middle East and North Africa to the main consumers in Europe. Such an increase in scale in the presence of large amounts of variable RES generation (mainly from wind and solar power) will require a clear regulatory framework, harmonised market structure and innovations in system planning, design and operation. It will also require reinforcements of existing electricity networks onshore. Transmission assets will thus continue to play a crucial role in connecting remote RES to customers and in managing the load-supply balance, along with more efficient and smarter use of energy by end consumers (ENTSO-E, 2010).

4. Conclusions

The steady-state analysis described in this article has been focused mainly on two topics: definition of the anticipated scenarios for the penetration of RES in the Sardinian power system by 2030, and the load flow analysis of the Sardinian grid in these scenarios.

The existence of several bottlenecks in the Sardinian network due to the demand and high RES production has been pointed out. A significant number of extreme system situations occurred in Sardinia where load and reserve requirements could not be met without curtailing RES generation. In fact, the scarcity of exporting capacity and the excess of power generation compared with load demand requires wind power production to be curtailed. Wind power curtailment is mainly caused by the need to keep adequate spinning and non-spinning reserve (the minimum power production of thermal power plants is the most cogent constraint to be complied with) and to avoid overloads of some critical grid branches. This leads to the outcome that for such extreme renewable penetration scenarios network reinforcements in Sardinia are required with the main focus on energy exports to the mainland of Italy.

Beyond the short/mid-term (until 2030) requirements for a well interconnected and smart grid including large-scale storage, electricity grids will have to evolve more fundamentally to enable the shift to a decarbonised electricity system, supported by new HV long-distance and new electricity storage technologies that can accommodate ever-increasing shares of renewable energy, from the EU and beyond (European Commission, 2010).

Finally, to meet the EU energy targets, significant research is required into the next generation of renewable energy and viable conventional generation technologies, and also into energy storage and overall system efficiency for the next 10 years (European Commission, 2007b; Battaglini et al., 2009). In addition, ambitious projects such as the European Supergrid and Desertec include relatively high RES integration in the European energy market that could lead to radical changes in both the nature and location of the main energy sources in the electricity system. Major investments in infrastructure and innovative technologies are needed (Verbong and Geels, 2010) and a new approach and new instruments could be required to ensure secure energy supply in the long-run.

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