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Smart renewable generation for an islanded system. Technical and economic issues of future scenarios

Valentina Cosentino [a,*], Salvatore Favuzza [a], Giorgio Graditi [b], Mariano Giuseppe Ippolito [a], Fabio Massaro [a], Eleonora Riva Sanseverino [a], Gaetano Zizzo [a]

[a] Department of Electrical, Electronic and Telecommunication Engineering, Chemical Technologies, Automation and Mathematic models (DIEETCAM), Università di Palermo, Palermo, Italy
[b] ENEA Research Centre, Portici (NA), Italy

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ABSTRACT

The subject addressed in this paper is the analytical study of the transition of an energy generation system for a real MV/LV distribution system from one that is “fuel-based” to a distributed and smart “renewables-based” system. The paper outlines both the technical and the economic issues related to such a transition from one type of system to the other. The study is carried out for a real islanded network located in the Island of Pantelleria (Mediterranean Sea). The results obtained are presented and discussed, putting into evidence the technical, environmental and economic benefits of using smart technologies and renewable energy sources.

1. Introduction

As it was underlined during the 2009 Major Economies Forum on Energy and Climate, “*moving to a low-carbon economy provides an opportunity to promote continued economic growth and sustainable development as part of a vigorous response to the danger posed by climate change*” [1]. Thus an urgent need has been identified for the development and deployment of clean energy technologies. In this framework, the most important challenge in the near future in the electrical power systems field, mainly for MV and LV (medium and low voltage) distribution systems, consists of the complete integration of DG (Distributed Generation). Considering the objectives fixed in the European Union for 2020 (a reduction of 20% of greenhouse gases and an increase of 20%, compared to the gross internal consumption, of electrical energy produced from renewable sources), one of the easiest ways to attain these objectives is with a considerable increase of DG within electrical systems [2]. This will allow the exploitation of the different renewable energy sources available in the territory that are otherwise not usable.

Nevertheless, the ever increasing penetration of DG in distribution systems encourages a rethink of all the design criteria, development, protection, control and management of resources in the transition from passive to active systems. At a national and international level, such necessary evolution will lead to the development of the so-called smart grids, suggesting with this term strongly automated systems that are characterised by the presence of dispersed generators, loads, storage systems and by control and management strategies that make use of ICT (Information Communication Technologies).

Within this framework, it is particularly important to perform studies and perspective research aimed at the evaluation of DG over the networks, both in technical terms and also through economic analysis. Several contributions can be found in the literature which analyse the technical, economic and environmental issues related to possible scenarios of the penetration of renewable sources for energy generation, at international, national and local levels [2–20]. The overall vision which comes for the aforementioned studies is that renewable distributed electricity generation can play a significant role in meeting various energy policy goals, such as greenhouse gas emissions reduction, energy security improvement,

* Corresponding author.
E-mail addresses: cosentino@dieet.unipa.it (V. Cosentino), favuzza@dieet.unipa.it (S. Favuzza), giorgio.graditi@enea.it (G. Graditi), ippolito@dieet.unipa.it (M.G. Ippolito), massaro@dieet.unipa.it (F. Massaro), eleonora.rivasanseverino@unipa.it (E. Riva Sanseverino), zizzo@dieet.unipa.it (G. Zizzo).

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and economic and industrial development. In this context, this paper presents some of the results of a technical and economic feasibility study concerning the transition towards active networks for an isolated medium voltage (MV) distribution network of the Island of Pantelleria (a small island in the Mediterranean Sea). The research work has been carried out by the DIEET (Department of Electrical, Electronic and Telecommunication Engineering, now DIEETCAM) of the University of Palermo, in cooperation with ENEA (Italian National Agency for New Technologies, Energy and Sustainable Economic Development), within the national research project ("Ricerca di Sistema" supported by the Ministry of Economic Development). The aim of the research was to contribute to the process of identification of new reference modes, and to the standardisation of relevant solutions for the transition from the present "fossil-fuel-based" energy generation system to a distributed and smart "renewable-based" scenario.

The study has been carried out in different phases. Firstly the electrical system under investigation has been analysed in terms of the production and consumption of electrical energy, articulation and consistency of the network, and the existing technologies for metering and automation, thus obtaining all the data needed to identify the initial or reference scenario.

Secondly, the local natural energy sources have been identified, and the main aspects have been analysed, related to the feasibility of the interventions finalised to the integration of renewables-based DG systems and the demand control. The relevant energy transformation systems have been suitably sized in order to meet the energy demand. The minimum and maximum sizes of the plants have been hypothesised, taking into account the particular features of the electrical system, the geographic location, the environmental constraints, the availability of space and the potential social acceptance. Starting from this, five different scenarios have been defined for the transition from fuel-based generation to the smart distributed renewable-based one. The control system has also been designed, and the main control functions as well as the telecommunication system have been hypothesised considering the relevant features of the installations.

Thirdly, a model of the network has been implemented and it has been used to carry out various simulations, with the aim of evaluating the system's performance under both normal working and under some particular fault conditions, for both the actual scenario and one of the defined scenarios, which has been chosen as a reference for the study.

Finally, the economic issues have been outlined, which are related to the transition from the fuel-based generation to the smart distributed renewable-based one. A costs–benefits analysis has been carried out for the chosen scenario. Benefits include environmental issues, incentives and other benefits deriving from the idea that the energy system can be truly integrated over the territory. A sensitivity analysis has been also performed, in order to take into account the most significant uncertainty contributions in the economic calculations.

The research findings are in concord with the previous literature, showing that renewables-based DG represents a real chance of improvement from environmental, energy and economic points of view.

2. Description of the system

2.1. Electrical system characterisation

The electrical system supplying the Island of Pantelleria is islanded and is characterised by a thermal power plant for the production of electrical energy, by a MV radial distribution network with 150 load nodes operated at the rated voltage of 10.5 kV. In more detail, other than the generation bus, it is possible to identify 133 substations, 2 switching substations and 15 supply buses for MV. The thermal power station is made up of 8 diesel groups, with a total power of about 20 MW. From the power station, 4 lines (aerial and cable) spread out, all supplying at MV the above reported substations and are indicated with progressive indices (Line 1 ÷ Line 4). Each line is equipped at the start of the line with maximum current and ground fault protection systems. The electrical distribution system, even if it is normally radially operated, shows different points where it is possible to radially counter-supply the lines, or where it is possible to create a meshed configuration, both inside certain substations that are currently remotely controllable, and from other points of the network.

Fig. 1 shows the simplified scheme of the MV distribution system where the four main supply lines are shown together with the substations in which remote control logics and faulted feeder detection have recently been implemented.

2.2. Electrical energy load

Currently, the Island of Pantelleria is completely dependent of external sources of energy, except for some small photovoltaic plants that have already been installed. The supply system is mostly composed of diesel, but also from oil and GPL. The power plant is composed of eight groups, for a total installed power of about 20 MW, with a loading factor of 0.18, as an effect of the alternate use of the different sections of the power plant. The annual energy need is about 44 GWh. Half of the yearly consumption of liquid fuel, for both transportation and energy production, takes place in-between June and September. In 2000, the need for liquid fuel was of about 10.2 MTEP (7.7 MTEP for the power plant) of which 4.8 MTEP was utilised during the summer (3.4 MTEP for the power plant). The analysis of the load diagrams shows that the peaks are registered in August during the evening (around 9 pm) and vary between 7 MW and slightly higher than 10 MW. In Fig. 2 the average hourly electrical power requests on a summer and winter day are shown. The minimum load can be registered during winter (January) at 3 pm, and is about 3.1 MW. The average power is about 6.2 MW during the summer and about 4.6 MW during the winter. The energy consumption in 2008 was of about 43.7 GWh, of which 24.4 GWh were used during summer (56%) (Fig. 3). (The data reported in Figs. 2 and 3 have been provided by the local electrical energy distribution operator and have not varied significantly in the last three years).

3. Feasibility study

With reference to the feasibility study for the integration of distributed generation systems, based on renewable sources and control of demand, a detailed study about the potential of the site has been carried out.

Among all the renewable sources available that can be fruitfully exploited, the choice of the most suitable ones has been made taking into account all the main aspects related to the constraints, availability of space, impact issues, territorial and functional specificity, etc.

Thus it has been decided to employ solar resources through photovoltaic conversion and thermal solar, as well as wind, the geothermal and urban waste sources.

3.1. Electrical generation from solar source through photovoltaic conversion

The Island of Pantelleria is characterised by a solar radiation of 1.69 MWh/m^2/year, with a minimum of 1.90 kWh/m^2/day in January and a maximum value of 7.2 kWh/m^2/day in July [21].

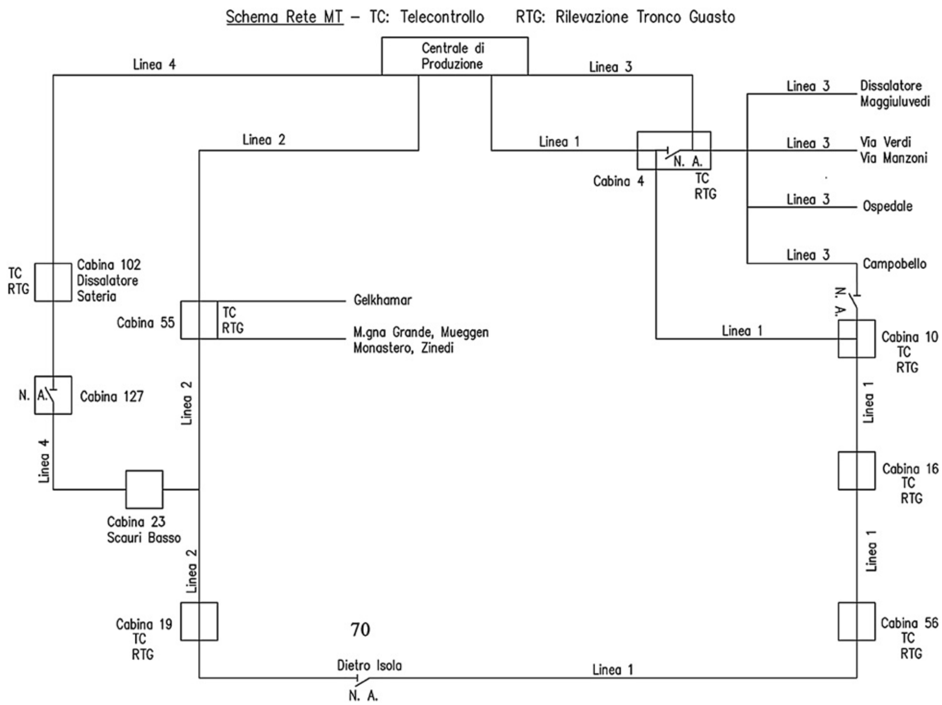

Fig. 1. Simplified scheme of the MV system.

Considering the particular environmental and architectural features of the island, and taking into account the truly available surfaces, it is possible to design the installation of photovoltaic systems in some specific areas for the following power and related energy capacity (for an equivalent number of hour of generation of 2007 h/year):

- Urban city (in the North): $P_{PV} = 750$ kWp – $E_{PV} = 1.17$ GWh/year;
- Industrial area: $P_{PV} = 300$ kWp – $E_{PV} = 0.45$ GWh/year;
- Airport: $P_{PV} = 50$ kWp – $E_{PV} = 0.08$ GWh/year.

Considering the contributions of all photovoltaic systems, it is possible to achieve a total power of 1.1 MWp, with a related electric energy capacity production of 1.7 GWh.

3.2. Electrical generation from wind sources

Pantelleria's characteristics of wind strength and frequency [22] make the production of electricity by wind generators suitable.

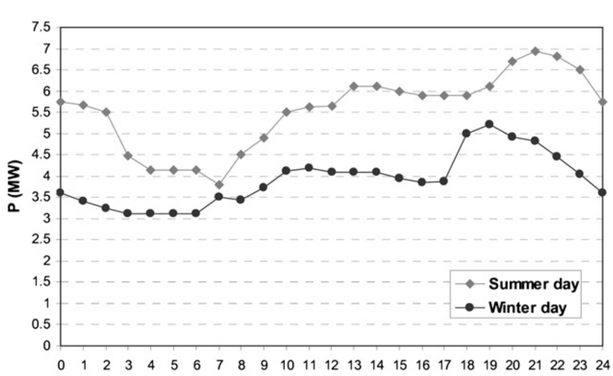

Fig. 2. Average hourly electrical power demand for a summer and a winter work day (2009).

However, the yearly trend of wind speed shows that the maximum wind resource power is during the winter, thus it is opposite to that of solar radiation and electricity demand. This has to be taken into account for the choice of the ratings of wind generators. In detail, in order to preserve grid stability, the power of such plants has to be correlated to the minimum winter load. In fact, in the case of sudden wind decline, a rapid response of the other power plants should be needed. However while in the presence of high winds and minimum loads, some of those plants would need to be kept steady, reducing the cost effectiveness of their installation. Furthermore, the effect of the environmental impact (for landscape constraints) should be also taken into account. All these reasons have identified a possible limited use of the wind resource. It is thus hypothesised to install up to two wind generators with a total rated power of 1.2 MW. Considering a unitary energy production of 3000 MWh/MW [22], the expected production of electrical energy can be evaluated as 3600 MWh/year.

3.3. Electrical generation from geothermal sources

In the past few years, many studies have been carried out on the Island of Pantelleria aimed at the use of geothermal sources

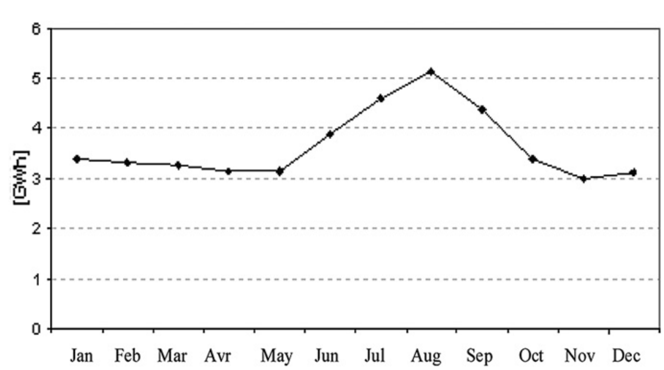

Fig. 3. Monthly electrical energy consumption (2008).

[23–26]. On the basis of these studies, it is possible to consider the realisation of a small geothermal power plant of 2.5 MW in the South–West of the island. Considering a system functioning for 8000 h/year, the obtainable energy is 20,000 MWh/year (about 46% of the total energy consumption of the island).

3.4. Electrical generation from urban waste

On the basis of executed studies, the refuse production is about 1.405 kg/day/inhabitant. Considering the number of inhabitants (about 7700), the population increase due to the summer tourist flows and the amount of not-recyclable waste (about 78%), the daily average not-recyclable waste production is reported in Fig. 4 [27]. On the basis of these data, it is possible to consider the installation of an urban waste electric generator near the rubbish dump in the South–Eastern part of the island. The generator size, determined on the basis of the daily refuse production, is 365 kWe. Assuming a heat combustion of about 4000 kcal/kg, for each ton of refuse it is possible to have an energy potential of 4600 kWh. Considering the system's performance and auto-consumption, the electrical energy that can be supplied to the electrical system is 1070 kWh/ton each hour; assuming a supply of 5 tons of refuse per day and a system functioning for 300 days/year, thus the energy supplied to the electrical system is about 1620 MWh/year [28].

3.5. Solar thermal source

In the curve trends of Fig. 2, a peak of power demand can be observed in the early evening (from about 6 pm to 10 pm). This is mainly due to hot water consumption (as at present hot water is mainly produced by means of household electrical water heaters). Thus, solar thermal plants for hot water production could lead to a concrete reduction in energy demand during those hours. Such plants can be installed both inside and outside the urban city (on building roofs or even at ground level). The hot water needs can be calculated in accordance with Refs. [29] or [30]. The application of the two methodologies determines an electrical energy consumption of 1380 kWh/year for each family. Assuming that about 75% of the island's families (2200) can use solar thermal systems, and that that these systems can satisfy 75% of the hot water needs, the electrical load of the entire island can be reduced by about 2.13 GWh. Considering that the equivalent number of functioning of solar thermal systems is about 2007 h/year, the average power related to the annual energy saving is about 1.06 MW.

4. Possibile scenarios

On the basis of the average electro-energetic needs of the PantelleriaIsland (44 GWh/year), five scenarios, reported in Table 1,

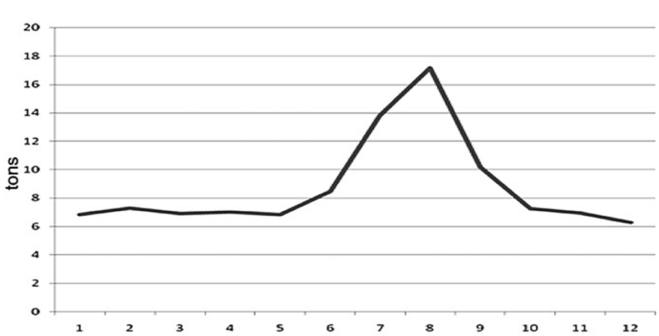

Fig. 4. Estimate of the average daily not-recyclable waste production each month [tons].

Table 1
Proposed scenarios.

Scen.	Source	[%] compared to max. power	Elect. power [MW]	Energy prod. [GWh/year]	Total Energy prod. [GWh/year]
10.1	PV	60	0.66	1.02	4.524
	Wind	50	0.6	1.80	
	Geoth.	0	0	0	
	Waste	0	0	0	
	Th. solar	80	0.848	1.704	
10.2	PV	60	0.66	1.02	4.324
	Wind	0	0	0	
	Geoth.	0	0	0	
	Waste	100	0.365	1.6	
	Th. solar	80	0.848	1.704	
20	PV	100	1.1	1.7	9.03
	Wind	100	1.2	3.6	
	Geoth.	0	0	0	
	Waste	100	0.365	1.6	
	Th. solar	100	1.06	2.13	
50.1	PV	30	0.33	0.51	23.175
	Wind	0	0	0	
	Geoth.	100	2.5	20	
	Waste	100	0.365	1.6	
	Th. solar	50	0.53	1.065	
50.2	PV	60	0.66	1.02	22.724
	Wind	0	0	0	
	Geoth.	100	2.5	20	
	Waste	0	0	0	
	Th. solar	80	0.848	1.704	

have been hypothesised [31]; in each of them a part of the energy needs is obtained from renewable sources. In particular, the first two scenarios are characterised by coverage of about 10% of the yearly electrical load of the island through renewable sources, in the third scenario this coverage is about 20% and in the last two scenarios the coverage is about 50%.

In Table 1, for each scenario, the typology of renewable sources, the size of the related plants, the percentage with respect to the maximum achievable size, and the relevant yearly production of energy, are reported for each renewable source and globally.

Among the scenarios, a technical-economic study has been carried out related to the scenario named 50.1, which is characterised by a coverage of 50% of the energy needs by means renewable sources. This scenario has been considered the most realistic among those defined, since it considers:

- The full exploitation of both the geothermal and waste sources (thus also allowing the best utilisation of waste, especially during summer time);
- The exclusion of the wind source, because, as already stated, it has its maximum during the winter when the electricity demand is lower and it is already covered by geothermal and waste sources;
- A limited amount of photovoltaic and solar systems, as their exploitation depends on the individuals' disposition to invest in such systems.

5. Simulations and results

Based on the characterisation, a model of the network has been implemented using NEPLAN simulation software. This software allows carrying out steady and dynamic simulations, short circuit calculations and so on (however, other commercial software tools are also available on the market for power systems simulations, such as PSCAD, DIgSILENT, EMTP-RV, PSS/E, SPARD, etc.). The model has been validated through a comparison between the output data of the initial or reference scenario (passive system) and those provided by the distribution operator. Then it has been used for load-flow analysis (under particular working conditions) and the short circuit study (for three phase faults at different nodes of the system), both for the initial scenario (passive) and for the scenario of the active network (with DG) selected, with the aim of evaluating the system's performance under such conditions.

Among the different working conditions, three extreme circumstances have been simulated:

A. Maximum load, 14 August, 9.00 pm, $P_{load} = 10.6$ MW;
B. Maximum photovoltaic production, 14 August, 12.00 am, $P_{load} = 7.8$ MW;
C. Minimum load, 14 January, 3.00 am, $P_{load} = 3.1$ MW.

Regarding the system topology, four principal points have been selected to create meshes:

- The tie-switch near the MV-LV station n.127;
- The tie-switch in bus 70;
- The tie-switch in bus 10;
- The tie-switch between line 1 and line 2 (airport connection).

Four possible configurations of interest have been considered:

1. The base passive radial system configuration;
2. The active radial one;
3. The totally meshed one (with the four abovementioned tie-switches closed);
4. The minimum meshed one (only one tie-switch closed).

In Fig. 5, the results of the simulations are reported. In particular, for each configuration and for each working condition ("Load. Cond" in the figure), the following quantities are reported:

- Real load power: P_{car} [MW]
- Load reactive power: Q_{car} [Mvar]
- Real power from diesel power plant: P_g [MW]
- Reactive power from diesel power plant: Q_g [Mvar]
- Real power from renewable sources: P_{gres} [MW]
- Reactive power from renewable sources: Q_{gres} [Mvar]
- Total power losses, both real and reactive: ΔP_{tot} [MW], ΔQ_{tot} [Mvar]
- Number of bus violations: num. viol.

In maximum load conditions (A), the base passive system (1) presents a high number of violations in voltage values. The power injections (in particular those coming from geothermal and waste generators) not only reduce the number of voltage violations (by about three times), but also halve the real power losses. The active configurations (3-totally meshed and 4-minimum meshed) allow also the elimination of voltage violations and the reduction of power losses.

In all working conditions studied, it is easy to note a great reduction in the power (both real and reactive) supplied by the diesel-oil plant. The voltage profiles analyses illustrate that the two

Conf	Load. Cond	Pcar MW	Qcar MVAR	Pg MW	Qg MVAR	PgRes MW	QgRes MVAR	ΔPTot MW	ΔQTot MVAR	Num. viol.
	A	10.6	6.273	11.404	7.03	0	0	0.804	0.757	119
1	B	7.8	4.616	8.193	4.814	0	0	0.393	0.198	35
	C	3.056	1.82	3.089	1.1519	0	0	0.033	-0.30	0
	A	9.799	6.273	7.615	5.325	2.574	1.229	0.39	0.282	37
2	B	7.41	4.385	4.748	4.314	2.897	0.059	0.235	-0.01	0
	C	3.056	1.82	0.639	0.635	2.574	0.957	0.157	-0.23	0
	A	9.799	6.273	7.496	3.36	2.574	3.027	0.271	0.114	0
3	B	7.41	4.385	4.628	3.274	2.897	0.963	0.115	-0.15	0
	C	3.056	1.82	0.542	0.541	2.574	0.957	0.06	-0.32	0
	A	9.799	6.273	7.547	3.789	2.574	2.659	0.322	0.174	0
4	B	7.41	4.385	4.652	3.445	2.897	0.827	0.139	-0.11	0
	C	3.056	1.82	0.555	0.554	2.574	0.957	0.073	-0.31	0

Fig. 5. Load-flow simulation results.

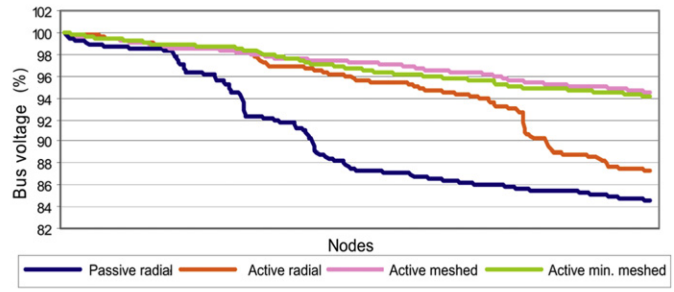

Fig. 6. Voltage profiles for the four configurations at maximum load conditions.

active configurations (3-totally meshed and 4-minimum meshed) present the best features for regularity in all the electrical system buses (see Fig. 6), limiting the voltage variations to a maximum of about 4%.

For the short circuit analysis, a three phase fault has been simulated, both in maximum and minimum load condition, in the following buses: diesel-oil plant bus-bar (G); geothermal plant bus-bar (125); waste generator bus-bar (129); bus n.127; bus n. 70; MV bus-bar of a MV/LV station (87) located in the urban centre.

The results are briefly summarised in Table 2: the values are normalised to the value of the three-phase short-circuit current obtained at the diesel-oil plant bus-bar (G) in the case of the passive network, which has been taken as a reference value for all other values of the currents. Furthermore, for the case related to the maximum load, the number of flow inversions of the fault currents is reported, with respect to the case of passive system. The analysis of the results gained from the simulations illustrates the high variation both in short-circuit current values and in power flow directions (i.e. power flow inversions with respect to the existing passive radial system).

Therefore, the connection of new generators requires a significant change in the present choices related to the characterisation and dimensioning of the protection systems. In greater detail, in the buses where the short circuit current increases, it is necessary to substitute the circuit breakers in order to provide adequate breaking power. Furthermore, in lines where the power flow

Table 2
Normalised values of short-circuit currents and power flow inversion.

Fault	Configuration	I_{cc3} (max)	I_{cc3} (min)	No. of inversions
Diesel-oil plant bus-bar (G)	Passive radial	1.000	0.333	–
	Active radial	0.774	0.276	53
	Active meshed	0.822	0.322	100
	Active min. meshed	0.786	0.314	72
Geothermal plant bus-bar (125)	Passive radial	0.146	0.118	–
	Active radial	0.293	0.265	0
	Active meshed	0.467	0.325	72
	Active min. meshed	0.346	0.306	44
Waste generator bus-bar (129)	Passive radial	0.108	0.094	–
	Active radial	0.123	0.106	28
	Active meshed	0.178	0.156	75
	Active min. meshed	0.167	0.109	47
Bus n.127	Passive radial	0.305	0.203	–
	Active radial	0.281	0.174	28
	Active meshed	0.490	0.295	75
	Active min. meshed	0.282	0.293	47
Bus n.70	Passive radial	0.123	0.103	–
	Active radial	0.221	0.210	0
	Active meshed	0.343	0.267	67
	Active min. meshed	0.286	0.234	39
MV bus-bar of a MV/LV station (87)	Passive radial	0.639	0.286	–
	Active radial	0.536	0.238	53
	Active meshed	0.595	0.284	95
	Active min. meshed	0.541	0.266	72

Table 3
Investment costs (C.1–C.4).

Cost (thousands of €)	Photo-voltaic	Geo-thermal	Waste	Solar	Control system
C.1	1320	8750	1825	2625	–
C.2	–	345	105	–	–
C.3	–	–	–	–	350
C.4	–	1819	386	–	70

direction changes, it is necessary to replace or install adequate directional protection. The economic implications of such changes have been taken into account in the following economic analysis (see Section 6).

6. Cost–benefit analysis for the selected scenario

For the considered scenario 50.1, an economic CBA (cost–benefit analysis) [32,33] has been carried out in order to evaluate the economic impact related to the transition from the current energy generation system to the aforementioned scenario. The costs and benefits related to the transition from a fuel-based generation to a smart renewable generation, according to the selected scenario, have been identified and evaluated. The analysis has been developed as a “project analysis”, i.e. taking into account all costs and benefits at large, without considering the subjects (even various) who would face the costs or profit from the benefits. This is a simplified assumption but it is well suited for the aim of the present study, which is to evaluate the overall impact of the smart energy generation, including not only the typical financial elements, but also the socio-economic aspects such as the environmental and health benefits.

6.1. Costs and benefits evaluation

The costs in the present study can be considered as follows:

C.1 Investment in the installation of the power plants;
C.2 Investment in the infrastructures needed for the plants' connection to the existing electric distribution network;
C.3 Investment in the control system;
C.4 Extra costs;
C.5 Yearly costs for energy production, management and maintenance of the power plants.

The monetary values of the aforementioned costs are listed in Tables 3 and 4. They have been derived from market analyses and the technical characteristics of the power plants, infrastructure and control system under consideration [34,35]. Cost C.3 also includes the investments in the adjustment of the protection systems to the new technical requirements (for short circuit currents and power flows) due to the presence of the new generators, in accordance with the results of the simulations reported in the previous section.

The extra costs (C.4) have been estimated as being equal to a value of 20% of the total investment cost in the geothermal and waste plants and the control system. For the photovoltaic and solar plants, costs C.2 and C.4 have been included in the investment C.1. The yearly costs (C.5) for the control system and the solar plants have been estimated to be equal to 1.5% and 2.5% of the investment cost C.3, respectively.

Table 4
Energy production, management and maintenance costs (C.5).

	Photo-voltaic	Geo-thermal	Waste	Solar	Control system
Energy production (MWh/year)	510	20,000	1600	–	–
Unitary cost (€/MWh)	80.00	80.00	100.00	–	–
Cost C.5 (thousands of €/year)	40.8	1600	160	65.6	5.25

Table 5
Benefits from reduction in electricity produced by the existing diesel plant (B.1).

	Photo-voltaic	Geo-thermal	Waste	Solar
Energy production (MWh/year)	510	20,000	1600	1065
Fuel cost (€/MWh)	40.00			
Benefit B.1 (thousands of €/year)	20.4	800	64	42.6

Regarding the benefits, they can be listed as follows:

B.1 Savings in the reduction of the electricity produced by the existing diesel plant;
B.2 Incentives for energy production by means of renewable sources;
B.3 Environmental benefits related to the savings in CO_2 and other greenhouses gas emissions and local environmental cost reductions;
B.4 Benefits related to different waste management.

Benefits B.1 (see Table 5) have been evaluated by multiplying the energy production of each renewable source by the cost of the fuel needed to produce the electricity with the existing diesel plant.

Benefits B.2 (see Table 6) have been evaluated by considering the monetary incentives currently offered in Italy [36,37] for energy production by means of renewable sources.

Benefits B.3 are related to the savings in CO_2 and other greenhouses gas emissions and in the reduction in local environmental costs, which are due to the production of energy by means of renewable sources instead of the traditional electrical generating system (the existing diesel plant).

With respect to this, in Ref. [38] it was shown how it is possible to find an equivalent CO_2 coefficient to quantify the emissions of each type of power plant. This coefficient considers the energy lifecycle emissions, including emissions associated with the construction of the plant, mining and processing of the fuel, routine operation of the plant, the disposal of used fuel and other waste by-products, and finally the decommissioning of the plant. In Table 7 the aforementioned emission coefficients for the different types of energy source considered in this study are reported, according to Ref. [38]. As a consequence, it is possible to evaluate the CO_2 reduction which is derived from the energy production by means of renewable sources instead of fuel-based ones. From an economic point of view, this reduction can be considered as both an externality (environmental benefit) [39] and a financial benefit (emission trading) [40].

A monetary evaluation of the environmental benefits has been carried out following the approach of the “ExternE, Externalities of Energy” Research Project of the European Commission [39]. In brief, the ExternE Project is aimed at the quantification of the so-called “external costs” of energy, providing a methodology for

Table 6
Incentives for energy production by means of renewable sources (B.2).

	Photo-voltaic	Geo-thermal	Waste	Solar[a]
Energy production (MWh/year)	510	20,000	1600	–
Incentives (€/MWh)	387.00	151.00	220.00	–
Benefit B.2 (thousands of €/year)	215	3020	352	289
Duration of incentives (year)	20	15	15	5

[a] The incentives for the solar plant consist in recovering 55% of costs C.1 in 5 years (11% for each year).

Table 7
CO_2 emission coefficients for the different energy sources.

Energy source	CO_2 emission coefficient (kg/MWh)
Photovoltaic	53.3
Wind	6.4
Geothermal	24
Waste	50
Solar (thermal)	53.3
Thermal (diesel)	935

transforming the impacts of the energy production into monetary values. In accordance with this study, the environmental benefits can be divided into two contributions: benefits to global warming, which are related to the savings in CO_2 emissions; and benefits to environmental impacts, caused by releasing either polluting substances (e.g. fine particles, SO_2, NO_X, CO, etc) or energy (noise, radiation, heat) into the air, soil and water. For the first contribution, the ExternE Project proposes the use of an avoidance costs approach, which leads to a central value of 19 €/ton CO_2; this value can be suitably incremented in order to also take into account the second contribution (environmental impacts) [38]. With regards to the financial benefits related to the saving in CO_2 emissions, the price of the tradable CO_2 permits has been taken into account, whose value oscillates between 10 and 20 €/ton of CO_2, depending on various factors such as climatic conditions, politic decisions, fuels cost, etc. [40]. By considering both externalities and financial issues, a monetary value of 25 €/ton of CO_2 has been considered in this study. Benefits B.3 are outlined in Table 8.

Finally, benefits B.4 are related to the use of waste for energy production. They have been evaluated by considering the cost avoided for the transfer of waste to the dump and disposal, which has been estimated to be equal to 150 €/ton. This avoided cost has been multiplied by the amount of waste to be used for energy production (about 1500 tons/year), thus obtaining an economic benefit of 225,000 €/year.

Other benefits can be identified concerning the reduction in energy loss and voltage drops at the grid level, and the advantages related to the implementation of smart control functions (reduction of interruption times, improvement of service quality, etc.). These benefits essentially have a technical nature and thus they have not been monetised in this project analysis, this is a pejorative hypothesis for the final results.

6.2. CBA parameters and results

In order to carry out the CBA, two basic parameters have to be chosen: the time horizon and the discount rate [33].

The time horizon is the maximum number of years for which forecasts are provided. It takes into account the economically useful life of the project and its likely mid/long term impact. In the case of long-life investment, like those of the case study, the forecasts should also take into account the various phases of construction, usage and disposal of the plants. Moreover, in the case study the incentives fruition periods also have to be taken into account, which are different for the various renewable sources. Thus, the time horizon for the CBA has been fixed to 20 years, which is the longest incentives fruition period (the one for the photovoltaic plants).

Table 8
Environmental benefits (B.3).

	Photo-voltaic	Geo-thermal	Waste	Solar
Energy production (MWh/year)	510	20,000	1600	1065
Coefficient of reduction of CO_2 emissions (kg/MWh)	882	911	885	882
Savings on CO_2 emissions (tons/year)	450	18,200	1400	940
Monetary value of CO_2 emissions (€/ton)	25.00			
Benefit B.3 (thousands of €/year)	11.25	455	35	23.5

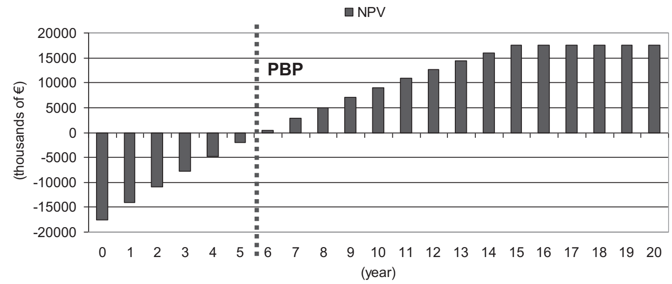

Fig. 7. Net Present Value trend and Pay-Back Period for the transformation of the energy supply system.

Table 9
Performance indicators.

Net Present Value NPV (thousands of €)	Internal Rate of Return IRR (%)	Pay-Back Period PBP (years)
17,514	18.65	5.75

With respect to the time horizon, the CBA should also take into account the residual value of the investments with a longer lifetime; this value should be considered among the benefits. For the sake of simplicity, the residual value of the investments has not been considered in the CBA, leading to pejorative final results.

Moreover, the CBA has been carried out assuming that all the investments are made at the beginning of the first year, and considering that all the investment and extra costs (C.1–C.4) are wholly incurred in year zero. This is a simplified assumption but it is well suited for the case study, as the CBA is mainly aimed to evaluate the maximum potential economic impact derived from the forecasted scenario.

The choice of the discount rate (i.e. the rate at which future values are discounted to the present) has been made by taking into account both economic and financial aspects related to the project analysis. As regards the economic issues, a social discount rate should be considered, as the project has an impact on the environment and, as a consequence, on social welfare [33]. On the other hand, the financial issues should be addressed by taking into account a financial discount rate (opportunity cost of capital), that can be different from the social discount rate [33]. For the present CBA a discount rate of 5.5% has been chosen, as it has been assumed to be a suitable trade-off between the financial and the social discount rates.

The economic tables are defined by the cash flows, which combine the inflows, outflows and balances for each year (from the initial time 0, i.e. the beginning of the first year of the time horizon to the final time of 20 years).

Table 10
Sensitivity analysis on benefit B1 (fuel cost). Performance indicators. Mean values and standard deviations.

	Net Present Value NPV (thousands of €)	Internal Rate of Return IRR (%)	Pay-Back Period PBP (years)
Mean value	20,200	19.69	5.61
Standard deviation	395	0.11	0.01

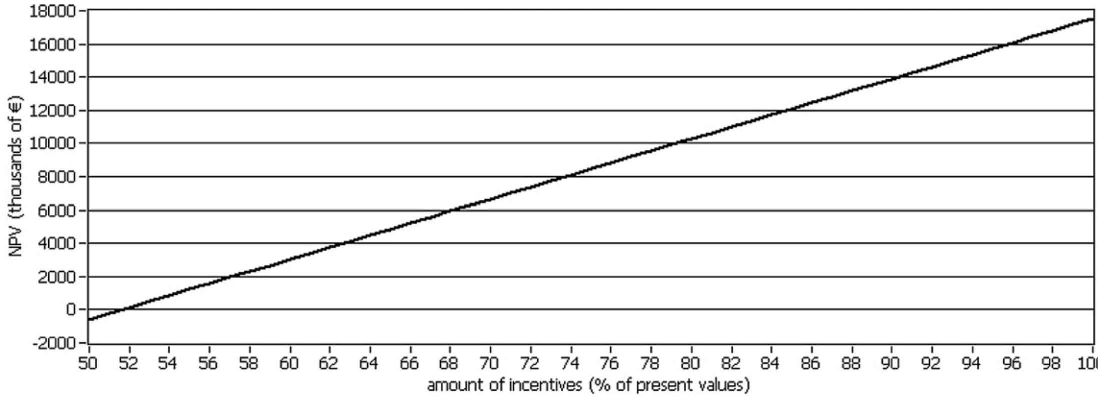

Fig. 8. Sensitivity analysis on benefit B2. Net present value trend by varying the amount of the incentives.

The performance indicator chosen for the CBA analysis are the NPV (Net Present Value), the IRR (Internal Rate of Return) and the PBP (Pay-Back Period).

The NPV of a project is defined as:

$$\mathrm{NPV}(S) = \sum_{t=0}^{n} a_t S_t = \frac{S_0}{(1+i)^0} + \frac{S_0}{(1+i)^1} + \cdots + \frac{S_0}{(1+i)^n}$$

where S_n is the balance of the cash flow at time n, a_t is the financial discount factor chosen for discounting and i is the discount rate (a_t is the coefficient for discounting a future financial value in order to have the actual value).

The IRR is the value of i that zeroes out the NPV of the investment. The PBP is the length of time required to recover the costs of the project.

The NPV trend over the whole time horizon of the project is represented in Fig. 7, where the Pay-Back Period is also shown (see the dot line in the figure); the values obtained for performance indicators are reported in Table 9.

It can be observed that the NPV is positive and the IRR is high if compared to the chosen discount rate. Moreover, the PBP is very short, thus the costs of the project can be recovered in a few years.

6.3. Main uncertainties and sensitivity analysis

An in-depth analysis of the economic calculations shows that the most influential parameters of the CBA final results are the fuel cost (see benefit B1) and the incentives for the energy production by means of renewable sources (see benefit B2).

Regarding benefit B1, a constant fuel cost has been considered for all the years of the time horizon in the economic calculations of Table 5. It is clear that this is a simplified assumption, which leads to an underestimation of benefit B1. In fact, in the last few years oil prices have risen dramatically and it is more than likely that it will continue to increase in the future [41]. However, it is quite difficult to forecast the dynamics of oil prices [42], as they depend on several factors, such as the amount of production and demand, economic crises, government policies, geo-political concerns and so on. With respect to this, in Ref. [43] some assumptions are given for international oil prices, for different policy scenarios and the forecasted range of variation in oil prices reported is very large (from 90 to 140 dollars per barrel), depending on the scenario considered. Thus, these forecasts have been taken into account for the sensitivity analysis of the CBA. In detail, a Monte Carlo analysis [20] has been carried out, by considering a rectangular probability distribution of the fuel cost inside the aforementioned range. The results of the calculations (10,000 trials) are reported in Table 10, where the mean values of NPV, IRR and PBP are shown, together with the related standard deviations.

Obviously, since an increase in the fuel cost has been considered during the time horizon, the CBA results obtained (mean values) are better than those reported in Table 9. Furthermore, it can be observed that the standard deviations are small if compared with the mean values; this means that the influence of the fuel cost uncertainty on the CBA results is weakly significant, as the main economic benefit is due to the incentives for energy production by means of renewables (thus the incentive policies are currently necessary to balance the investment costs for renewables).

With respect to the incentives, a sensitivity analysis has been carried out, in order to investigate their lower limit which still makes the investment economically feasible (i.e. which leads to a positive NPV). For this purpose, the same reduction has been applied for all present incentives. The results of this analysis are reported in Fig. 8, where the x-axis reports the amount of the reduced incentives (in percentage of the current values) and the y-axis reports the corresponding NPV (which was evaluated in the case of constant fuel cost). It can be observed that the investments are still feasible with incentives of up to 52% of the current values. It is clear that this threshold would be lower if the increase in fuel cost were considered, this indicates that the economic advantages of the renewable sources (besides the environmental ones) will increase in the future.

7. Conclusions

In this paper an analytical study has been presented concerning the transition of an energy generation system for a real MV/LV distribution system from a “fuel-based” one to on that is distributed and smart “renewables-based”. The real power system studied is located on the Island of Pantelleria (Mediterranean Sea). The attention has been focused on both the technical and the economic issues related to such transition.

In particular, a technical analysis has been carried out for a specific scenario characterised by renewable sources that are truly usable. The results gained from the simulations highlighted the benefits due to the evolution of the present electrical system in an active one, both in terms of loss reduction and of quality of the energy supply. Nevertheless, an actual implementation of future evolutionary scenarios of the present system needs extensive structural and control modifications.

On the subject of economic issues, a cost–benefit analysis has been carried out for the selected scenario of transition. The analysis has included not only the traditional financial aspects, but also environmental issues, incentives and other benefits derived from the idea that the energy system can be truly integrated over the territory. The results of the analysis are positive, demonstrating that the deployment of smart and clean energy technologies represent not only a big opportunity for sustainable development, but also a cost-effective investment.

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