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Environmental assessment of 2030 electricity generation scenarios in Sicily: an integrated approach

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Abstract

This paper deals with the environmental assessment of two electricity scenarios in Sicily, for 2030, characterized by a high exploitation of renewable energy sources in order to quantify the potential contribution of the local strategies in the achievement of the European climate policies and the potential improvement in the future electricity mix, compared to the current one (2014). In order to match these goals, authors integrate the Life Cycle Assessment with a scenario analysis. The future electricity mix scenarios, characterized by a share of renewables (57% for 2030-BS scenario and 51% for 2030-DS scenario) show a reduction of the greenhouse gases emissions per kWh of electricity generated, compared to the current one in which renewables account for 24%. Greenhouse gases emissions decrease by 39.9% in 2030-BS and by 32.9% in 2030-DS. However, the analysis highlights that the state of development of technologies does not allow improvements in a whole set of impacts categories. Particularly, freshwater ecotoxicity increases by around 30% and resources depletion by more than 100%. Results of this study can be used by local authorities as knowledge base in the definition and "ex-ante" evaluation of site-specific low-carbon energy strategies in Sicily.

Keywords

Electricity scenarios, energy policy, renewable energy sources, life cycle assessment, environmental sustainability, marginal electricity generation technologies.

1 Introduction

The need of a decarbonized, resource-efficient and biodiverse economy for fighting climate change and the loss of ecosystems and biodiversity [1] is quickly becoming a priority in research as well as, although on a slower pace, in political agendas.

Europe is one of the leading forces in the ambitious decoupling of the degradation of the environment from the improvement of health, welfare and well-being [1]. The EU is in fact already taking actions to curb greenhouse gas (GHG) emissions in most economic activities. In particular, since 2007, Europe has identified priorities for action in the Strategic Energy Technology Plan (SET Plan) with the aim to accelerate the decarbonization and environmental sustainability of the energy sector [2,3], which is responsible of roughly two-thirds of all anthropogenic GHG emissions [4].

The clean energy transition should give birth to an energy system where primary energy supply would largely be generated from renewable energy sources (RES) [5] and, as a milestone towards this goal, the use of RESs is expected to represent at least 27% of European energy consumption within 2030 [6].

Focusing on the energy use, by 2050 the share of electricity in the final energy demand will at least double, bringing it up to 53%, and more than 80% of electricity will be from RES (increasingly located off-shore) [5].

The decarbonization of electricity is a key component of mitigation strategies aimed at the reduction of the levels of carbon dioxide concentration in the atmosphere in most integrated future effects of climate change modelling [7], and it is one of the means towards several of the seventeen Sustainable Development Goals (SDGs) of the 2030 Agenda for Sustainable Development envisaged at the United Nations Sustainable Development Summit on 25 September 2015 [8], like SDG 7 “Affordable and Clean Energy and SDG 13 “Climate Action”.

Furthermore, decarbonizing the electricity supply and increasing electricity end-use efficiency are two key components of the 2°C Scenario (2DS) defined in the “Energy Technology Perspectives 2014” by the International Energy Agency (IEA), where the achievement of the 2DS targets is connected to a decrease by 90% within 2050 of the CO_2 emissions per unit of electricity [9].

However, in order to achieve the ambitious goals of the economic decarbonization, it is necessary to start from local actions while trying to involve in the process regional and national authorities: developing tailored site-specific actions on the local scale is needed to achieve results on the global one.

Moreover, it is important to assess the potential energy and environmental benefits of future local electricity generation scenarios, which are characterized by an increase in the contribution of RES to the energy generation mix [10].

In defining future electricity scenarios, it is paramount to issue forecasts and simulations based on realistic hypotheses. Moreover, the assessment of the energy and environmental impacts should be performed taking into account the development of the electricity generation technologies.

In this context, this paper presents a scenario analysis for electricity generation in Sicily in 2030, with the aim to evaluate the potential improvement in the eco-profile of grid-electricity generation through a life cycle approach and to quantify the contribution of the Sicilian electricity mix in the achievement of the European energy and environmental impacts reduction goals.

The Sicilian electricity mix scenarios for 2030 are defined through the identification of the so-called "marginal" electricity technologies for the energy sector. A marginal technology is defined in Weidema et al. [11] as "a technology actually affected by a small change in demand". Specifically, it is a technology able to regulate its output, increasing it if the related market trend increases as a result of the change or vice versa.

The authors applied the Life Cycle Assessment (LCA) methodology to assess the energy and environmental impacts connected to the whole life cycle of the electricity generation and its indirect impacts.

LCA is widely applied by the scientific community for the assessment of environmental impacts related to electricity generation technologies [12] [13] [14] [15].

The improvement of the electricity eco-profile in the future scenarios is assessed by comparing it with the electricity eco-profile of 2014, assumed as reference year, since it is the year with a more detailed available data on electricity generation among the most recent data available.

The paper contributes to the state-of-the-art providing one of the first applications of the LCA methodology integrated with a scenario analysis in the Italian context, aimed at quantifying the sustainability of future electricity generation scenarios at regional scale (Sicily) and its contribution on the achievement of the EU energy and environmental goals and on SDGs 7 and 13. The future electricity mix scenarios are based on the identification of the marginal electricity technologies for the examined local contest based on the energy and climate policy and on the site-specific data about unexploited energy sources. Data and results of this study are site-specific eco-profiles of current and potential future electricity mixes developed by taking into account the needs and the peculiarities of the local context that can support national and local decision makers in the definition and evaluation of low-carbon energy strategies. The results can support the EU decision makers in the continuous improvement of the climate policies for Member States. In addition, the results can be used by LCA practitioners for the study of products/services that involve the use of electricity in the regional context, in current and/or in future oriented studies. The availability of site-specific electricity mix studies can significantly improve the environmental assessment of the products/services involving electricity consumption.

The paper is organized as follows. Section 2 presents a literature review on environmental analyses of future electricity generation scenarios. Section 3 describes the data and the procedures for the definition of the electricity scenarios in Sicily. The application of the LCA methodology to the future electricity mixes and the obtained results are illustrated in Section 4. Section 5 shows the potential contribution of the Sicilian electricity sector to the targets of the 2030 European Union climate and energy package. Section 6 provides some final remarks.

2 Literature review

Several studies are available in literature assessing the environmental burdens due to the energy generation in future forecasted scenarios through a life – cycle approach. Some are specifically focused on the electricity sector and are briefly discussed in the following paragraph in order to provide a review of the existing framework in the field from a methodological perspective and with a specific focus on life cycle impacts assessment.

Regarding the first aspect, Burchart-Korol [16] build future electricity scenarios in Czech Republic and Poland in 2030 based on International Energy Agency (IEA) energy policies reports. Treyer and Bauer [17] defined future electricity scenarios for United Arab Emirates (UAE) in 2030 by considering the forecasted electricity demand, technical constraints to renewable energy sources employment and the energy policy goals inferred from UAE report. Turconi et al. [18] considered two future electricity scenarios in Denmark in 2030 considering in one case the climate targets set by the European Union and the Danish government and in the other a ‘business as usual’ trend. The two future scenarios were defined by taking into account the expected electricity demand growth, the dismantling of existing power plants, and the development of technologies used for power generation. Stamford and Azapagic [19] investigated five scenarios on the evolution of the United Kingdom (UK) electricity mix from 2009 to 2070. The scenarios were characterized by different percentage reductions in GHG emissions for electricity generation and considering the electricity generation technologies expected to play a major role in the future. Felix and Gheewala [20] build future electricity scenario in Tanzania in 2030 considering the forecasts developed by the national electricity supply company. Dandres et al. [21] considered two EU energy scenarios: a business as usual scenario, where energy policies set in 2000 were extended to 2025; and a “bioenergy scenario”, based on a significant increase (from 2 Mtoe to 22 Mtoe) in biomass utilization and a reduction of EU demand for coal. The authors considered the evolution of European energy markets by applying a partial equilibrium economic model.

The analysis of the studies described above highlighted that the approach followed in defining future electricity generation scenarios does not always consider the electricity demand trend or the effective technical potential of the energy sources in the future. However, in order to support the decision-making process, the analysis of future electricity mix scenarios should be based on site – specific data about the exploitable technical potential of the different energy sources, the electricity demand trend and the planned energy policies.

Regarding the second aspect, three of the examined studies assessed the environmental impacts related to the future electricity generation by using LCI data on the current electricity generation technologies [16] [18] [20]. Treyer and Bauer [17] modelled the technology improvement of the natural gas combined cycle power plants by extending their lifetime. However, they considered the current eco-profile to assess the environmental impacts related to the other electricity generation technologies. Stamford and Azapagic [19] assumed that the thermal power plants can be considered a relatively mature technology so that they used the same LCI inventory for both the current and future scenarios. The technological development of the PV power plants was modelled by considering energy efficiency improvement in the examined period. Dandres et al. [21] modelled the technological evolution starting from the dataset available in the Ecoinvent database by increasing the efficiency of each technology based on yearly average growth rates found in literature.

Regarding the LCI, using data that take into account the future electricity generation technologies development could provide more reliable results on the associated environmental impacts. In this context, an example is the New Energy Externality Developments for Sustainability (NEEDS) project [22] in which scenario-based LCI databases of future technologies was developed. However, in the case of emerging technologies the level of knowledge does not permit reaching accurate environmental assessment results [23] [24]. Thus, when the aim is to support the decision makers in a short – medium period context, in the authors ‘opinion, a possible approach is to assume a precautionary scenario and to use LCI data of the current and well-established technologies.

In this context, the authors perform an analysis of the potential available exploitation of renewable energy sources at regional scale by using site – specific data and they investigate two future electricity scenarios considering the forecasted electricity demand trend and identifying the potential marginal electricity generation technologies for the short – medium period. They integrated the scenario analysis with the LCA methodology in order to evaluate the environmental sustainability of the foreseen scenarios compared with the current one. The environmental impacts related to the future electricity generation technologies are calculated by using the LCI referred to the current ones.

3 Electricity generation scenarios

This section describes the steps followed to define future electricity generation scenarios in Sicily, characterized by a high exploitation of renewable energy sources.

In detail, the procedure followed can be recapped in four main steps, as in Figure 1.

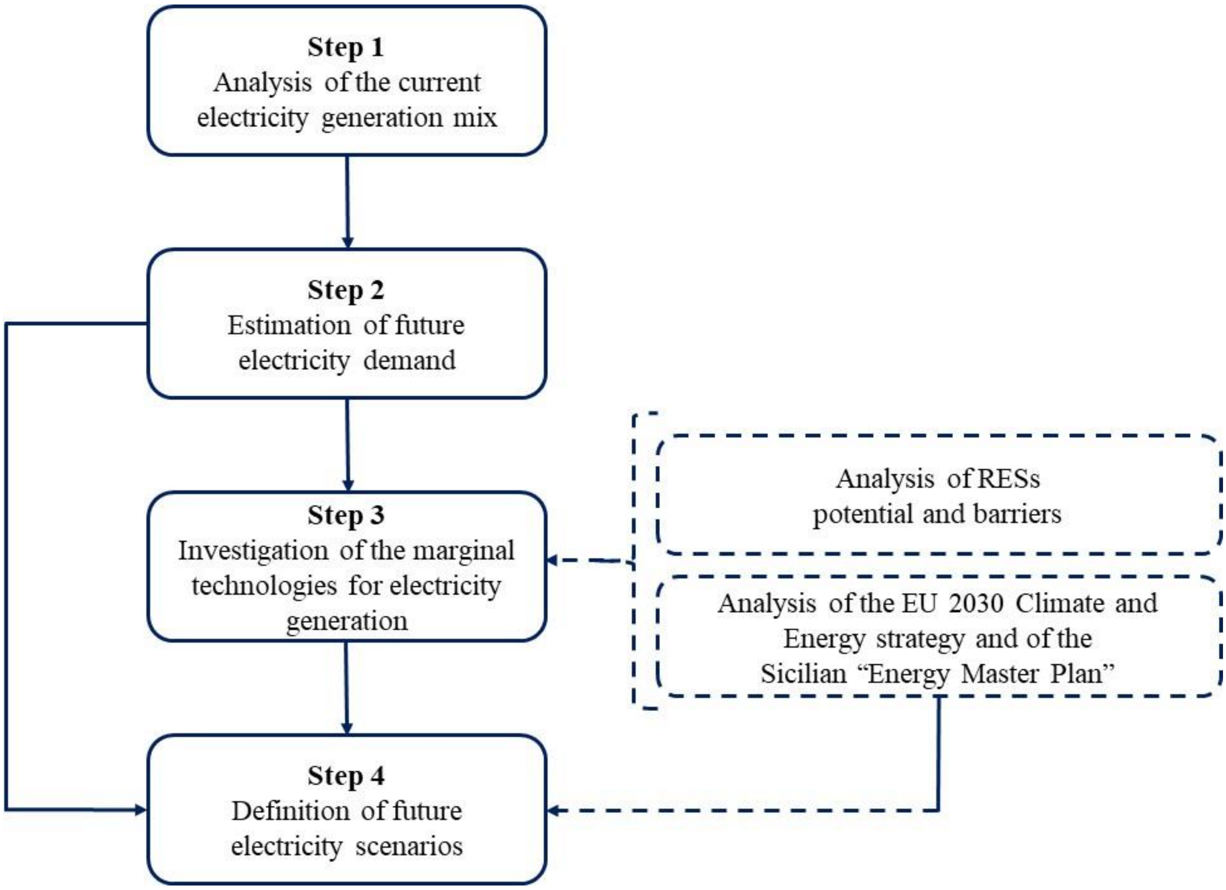

Figure 1. Steps for the definition of electricity generation scenarios.

- Step 1 – Analysis of the current Sicilian electricity mix. The aim of this step is to assess the level of renewable energy source exploitation in the current state.
- Step 2 – Estimation of future electricity demand. In this step the analysis of the potential evolution in the short – medium period of the electricity demand in Sicily is carried out.
- Step 3 – Selection of marginal technologies to be used for electricity generation. The energy marginal technologies are selected on the basis of the assessment of the potential development of each renewable energy source compared with the current level of exploitation.
- Step 4 – Electricity generation scenario definition. In this step, the quantitative and qualitative data collected in the previous steps are merged to define electricity mix scenarios in compliance with the European Union climate and energy policies.

In the following sections each step is described with higher detail.

3.1 Step 1 – Analysis of the current electricity mix

In the first step, data on the energy sources and technologies used in Sicily for the electricity generation is collected with the aim to depict the Sicilian current electricity mix and to assess the current level of renewable exploitation in the island. Data is obtained from two sources: the grid operator for electricity transmission in Europe (TERNA group), which publishes statistics on electricity generation at the regional level in Italy [25], and the Italian authority of energy services (Gestore dei servizi energetici - GSE), with a particular focus on the annual statistical reports on the diffusion of the renewable energy systems [26].

In Sicily, electricity is generated by thermal (gas combined cycle, steam - turbine, gas turbine, combined – cycled power plants and Integrated Gasification Combined Cycle (IGCC) power plants), hydroelectric, wind and photovoltaic power plants [27].

Table 1 shows the gross electricity generation in Sicily from 2009 to 2014 disaggregated by technology and energy source, except for the electricity generation in pumped storage units from water previously pumped uphill [28]. 2017 data from TERNA and GSE is available. However, disaggregated data on the thermal power plants is only available up to 2014.

Thus, the electricity mix in 2014 is assumed as reference (Reference Scenario - RS). In 2014, the total installed power was 9463.7 MW (60% thermal power plants, 18.6% wind, 13.7% of solar PV and 7.7% hydro power) [25].

The analysis of the data from 2009 to 2014 shows a progressive increase of renewable energy sources driven by support policies and more stringent environmental regulations.

More in detail, the gross electricity production by power plants in Sicily from 2009 to 2014 is mostly based on thermal power plants fuelled by fossil sources, which account for more than 70% of the whole production in the RS. The share of natural gas is around 50% during all investigated years while the contribution of oil products decreased from 32% to about 12%. The electricity generation from renewable energy sources increased significantly between 2009 and 2014. Specifically, the share of renewable, equal to 7% of the total electricity production in 2009, increased up to about 24% in 2014.

Table 1. Sicilian gross electricity production (GWh) disaggregated by type of power plant and energy source (2009 – 2014) (own elaboration based on TERNA and GSE data [25] [26]).

Type of facility	Gross electricity generation (GWh)					
	2009	2010	2011	2012	2013	2014
Hydropower - run of the river	104	144	98	172	175	146
Photovoltaic	33	97	670	1512	1754	1893
Wind	1444	2203	2370	2996	3010	2922
CHP* - natural gas	2393	4647	4339	4460	4395	4776
CHP - oil products	2282	2091	2313	1769	1095	907
CHP - other fuels (solid)**	2204	3499	3571	4057	4161	3319
Power plants - natural gas	9260	7947	7934	6736	6365	6113
Power plants - oil products	5316	3058	2593	2011	1906	1875
Bioenergy*** (CHP + Power plants)	114	150	110	70	190	259

Total production	23,150	23,836	23,998	23,783	23,051	22,210

[*]CHP: combined heat and power plant.

[**]Other solid fuels: brown coal briquettes, coke, etc.

[***]Bioenergy: biogas, biomass and bioliquid.

3.2 Step 2: Estimation of future electricity demand

The prediction of the Sicilian electricity demand in 2030 is based on a report developed by TERNA [29]. In this report, the forecast of electricity demand is based on a macroeconomic approach which analyses the economic evolution of the country (gross domestic product (GDP), sectoral added value, expenditure on household consumption and the growth in energy demand in the various sectors of activity).

TERNA proposes two possible scenarios for future electricity demand in Italy. The first one, named as “Base scenario” (BS), is based on an estimated GDP growth of 0.9% and on the full implementation of energy efficiency policies for which the electricity intensity decreases by 0.5%. This scenario involves an estimated decrease of the electricity demand with an average annual rate of 0.1% in the major Italian islands. The second one, named as “Development scenario” (DS), is based on an estimated gross GDP of 1.3% and on the partial implementation of energy efficiency policies (electricity intensity decreases by 0.4%). BS involves an estimated increase of the electricity demand with an average annual rate of 0.6% in the major Italian islands.

On the basis of the previous assumptions, the electricity demand in Sicily is estimated to be 21,857.3 GWh in BS, and 24,440.8 GWh in DS.

3.3 Step 3: Marginal electricity production technologies

In this step, the authors identified the marginal electricity technologies for the Sicilian energy sector, based on the need to increase the renewable energy source penetration in the near future.

A marginal technology is a technology able to adjust its energy generation rate to meet the changes in demand [11]. Its capacity can be adjusted without being subjected to natural capacity (e.g. availability of land in the case of energy crop production) or political constraints (e.g. GHG emission limits for fossil fuels thermal power plants). Identifying the marginal suppliers of electricity is crucial for the analysis, as it allows for the formulation of more realistic assumptions among all kinds of future scenarios. However, this process may present a certain number of challenges because it requires not only the knowledge of the local production capacity, but also a thorough understanding of the energy regulations and politics affecting the regional and local electricity production [30].

The EU energy and climate objectives for 2030 aim at cutting GHG emissions by 40% if compared to 1990 levels, and at increasing renewable energy use up to 27% [6]. In addition, on the 2018 Katowice UNFCCC Conference (COP24) the European Parliament supported updating the EU's target to reduce GHG emissions to 55% below 1990 levels by 2030.

As for all the European countries, the future development of the Italian, and consequently, of the Sicilian electricity sector will be driven by the need to reduce the GHG emissions and to increase the share of renewable energy sources. Thus, the short – medium marginal electricity production technologies should be renewable energy technologies. However, also the thermal power plants fuelled with fossil fuels can fulfil the role of marginal technologies since the electricity production from these power plant should decrease in order to achieve a more sustainable and secure energy sector. In fact, in case of decreasing market, like as the market of electricity production from fossil fuels due to the climate policy, the marginal technology is a technology able to provide a reduction in production capacity to meet the changes in demand [11].

In this paper, the identification of the renewable energy marginal technologies is performed considering the following factors:

a) renewable energy sources penetration in the Sicilian electricity production mix in the reference scenario;
b) EU climate and energy policies and local Sicilian energy strategies;
c) unexploited renewable energy sources technical potential, i.e. achievable energy generation of a particular technology given system performance and technical constraints (environmental, topographic, land use, etc.) [31].

The assessment of the technical potential for exploitation of renewable energy sources in Sicily is carried out in order to establish an upper-boundary estimate of potential development, and the achievable increase of each renewable energy source compared with the level of exploitation of the reference scenario (2014).

In the following paragraphs, the authors carry out an assessment of the technical potential of each technology and the barriers to their diffusion, based on scientific and technical reports referred to the Sicilian context [32] [33] [34]. The analysis, based on site – specific data, allows to identify the renewable marginal electricity generation technologies for the Sicilian energy sector. In addition, the authors estimate the production from each technology in 2030 based on the data collected from the "2030 Sicilian Energy Master Plan" as it is the most updated and site – specific available data source on the Sicilian energy sector transition toward the 2030 energy and climate goals.

Hydropower. The barriers are mainly due to the high initial investment cost, low social acceptance due to aesthetic impacts of hydropower – related facilities (including dams, pipelines, etc.), impacts on the eco-system [35] and the need to consider other water – using sectors (e.g. agriculture, domestic and industrial uses) [36] [37] [38].

In the Sicilian "Energy Master Plan", the foreseen increase of hydropower is considered negligible, since the largest part of the available technical potential has been already exploited, and the potential of small hydro is very limited [34,39] [32].

From the above-mentioned consideration, the hydropower technology was not considered a marginal technology for the Sicilian electricity sector in the short – medium period.

Wind. Barriers to wind farm development include high capital costs and the uncertainty related to public financing, impacts of its intermittent generation on power system reliability, insufficient grid connection capacity, a lack of planning for grid extension and reinforcements, and low social acceptance to local wind farm development due to the visual impact and land ownership [40] [41]. The potential for future exploitation of wind resource in Sicily was based on three Italian studies [42], [33] [43]. The first two assessed the potential electricity generation from wind energy, excluding the areas subjected to environmental constraints (e.g. protected areas) and technical constraints (e.g. soil topography). The estimated potentials were referred to 2020 and are equal to 3.79 TWh in Benini et al. [33] and to 3.51 TWh in Alterach et al. [43], marking a variation of 30% and 20% to the wind generation in 2014, respectively. More updated data were inferred from ANEV (ANEV, 2018) and from the 2030 Sicilian Energy Master Plan [32] which provided forecasts referred to 2030. Specifically, ANEV forecasted an installed power equal to 2000 MW in Sicily. Considering a specific annual energy production at 75 m a.t.l[1]./a.s.l.[2] of 2000 MWh/MW [44], an electricity generation of 4000 GWh can be forecasted for an installed power of 2000 MW. Indeed, in the 2030 Sicilian Energy Master Plan an installed power of 3000 MW was forecasted for 2030 with a corresponding energy electricity production of about 6117 GWh. The increase in energy produced will be achieved through the revamping and repowering of existing plants and the installation of new plants. Since the installed power was 1700 MW, in 2014 wind power plants can be considered marginal technologies for the Sicilian electricity sector in the short – medium period.

With regards to offshore wind power plants, due to the significant impact of these infrastructures on some of the main activities of the Sicilian economy, such as fishing, tourism and bathing areas [27], the authors assumed that they cannot be considered electricity marginal technologies in the short – medium period.

Solar photovoltaic. In the past, the penetration of this technology was constrained by the high cost (and the related incentives), and the acceptability of the impacts (e.g. visual) involved mainly in the case of ground mounted systems. Concerning the first aspect, according to a report developed by the International Renewable Energy Agency (IRENA),

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[1] Metres above terrestrial level

[2] Metres above sea level

the cost of solar PV could fall by more than half in the next ten years, driven by technological developments, economies of scale, etc. [45]. Thus, the cost could no longer be a constrains for the solar PV technology. Concerning the second aspect, the constraint of the visual impact has already been overcome by the diffusion of the building integrated PV systems.

The potential contribution of solar energy estimated in the 2030 Sicilian Energy Master Plan [32] is 5950 GWh corresponding to an installed power of about 4000 MW. This increase in energy generation will be achieved through the revamping and repowering of existing plants and the installation of new plants in marginal areas, such as quarries, mines and exhausted landfills. Furthermore, part of the new electricity production will be obtained from building integrated photovoltaic systems. Then, the solar photovoltaic technology can be considered a marginal technology in the short – medium period, since within the renewable technology sector, solar power seems to be the most promising, considering the Sicily high solar irradiation (Figure 2) [46,47] and the exploitable potential discussed above.

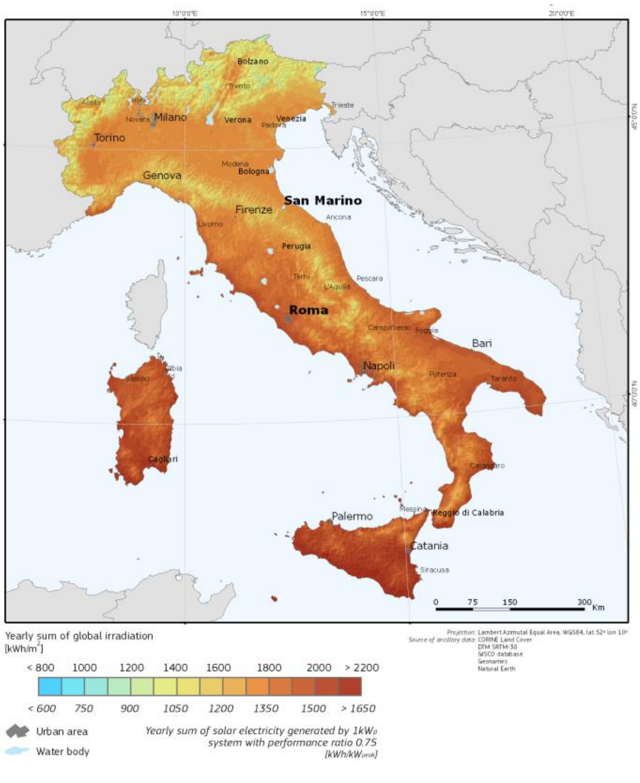

Figure 2. Yearly sum of solar electricity generated by 1 kW_p system [48].

Bioenergy. Main barriers to bioenergy thermal plants are, conversion efficiency, feedstock availability, lack of logistics supply and the competition between bioenergy utilisation for energy generation and food production [49] [50].

The electricity production in Sicily from bioenergy was 259.2 GWh in 2014. Benini et al. [33] estimated that the potential electricity generation from thermal plants fuelled with bioenergy in Sicily in the short period will increase up to 795 GWh. The Sicilian Energy Master Plan discusses the potential for exploitation of bioenergy for electricity and heat generation, estimating that in a medium – long term a surface of about 300,000 ha may be available for energy crop [34]. In addition, in the last updated Sicilian Energy Master Plan, electricity production from thermal plants fuelled with bioenergy of about 300 GWh was estimated for 2030. On these bases, thermal plants fuelled with bioenergy were considered a marginal technology for the Sicilian energy sector in the short – medium period. According to the above considerations, the level of exploitation of the marginal renewable energy sources is recapped in Table 2.

Table 2. Level of exploitation of the marginal renewable energy sources foreseen in 2030.

Marginal electricity technology	Estimated production in 2030 (GWh)	Estimated increase compared to RS (%)
Photovoltaic	5950	214
Wind	6117	109
Bioenergy	300	16

When the production foreseen in 2030 for photovoltaic, wind and bioenergy technologies will be achieved, they would become constrained technologies and therefore no longer marginal for the Sicilian energy sector

3.4 Step 4: Future electricity scenarios definition

The electricity generation mix scenarios in Sicily for 2030 are defined considering the installation of the available technical potential from the marginal electricity technologies discussed in Section 3.3.

Two scenarios, named 2030-BS and 2030-DS, are defined considering the BS and the DS evolution of the future electricity demand, respectively.

In both 2030 scenarios, hydropower is not considered a marginal electricity technology as discussed in Section 3.3. The amount of electricity generated from hydropower in 2030 is assumed equal to the average production between 2009 and 2014 (150 GWh). Photovoltaic, wind and bioenergy power plants are considered marginal technologies (Table 2).

The assessment of the electricity generation from thermoelectric plants fuelled with fossil fuels is based on the difference between the forecasted renewable energy production and the forecasted energy demand in 2030. The percentage distribution of each technology in the thermoelectric sector is considered unchanged if compared to RS. Table 3 shows the electricity mix in RS and forecasted in 2030 – BS and 2030 – DS developed in compliance with European energy strategies as they reduce the fossil fuels dependence increasing renewable energy sources penetration.

Table 3. Electricity mix in the RS, 2030 – BS, 2030 – DS.

Type of plant	RS (%)	2030 – BS (%)	2030 – DS (%)

Hydropower-run of river	0.7	0.7	0.6
Photovoltaic	8.5	27.2	24.4
Wind	13.2	28.0	250
CHP[*] -natural gas	21.5	12.0	13.7
CHP - oil products	4.1	2.3	2.6
CHP -other fuels (solid)[**]	14.9	8.3	9.5
Power plants - natural gas	27.5	15.4	17.6
Power plants - oil products	8.4	4.7	5.4
Bioenergy[***] (CHP + Power plants)	1.2	1.4	1.2

[*] CHP: combined heat and power plant.

[**] Other solid fuels: brown coal briquettes, coke, etc.

[***] Bioenergy: biogas, biomass and bioliquid.

Both the foreseen electricity mix scenarios, are characterized by a high share of renewables (57% for 2030 – BS scenario and 51% for 2030 – DS scenario).However, scenarios with high penetration of renewable energy sources will require a further expansion of the grid technical capabilities [32] and the implementation of energy storage technologies on a local scale [51,52] [53] [54] able to manage the variability in renewable energy sources output and to guarantee a more stable electricity system [55].

4 Life Cycle Assessment

4.1 Goal and scope definition

The goals of the LCA study are:

- to evaluate the potential improvement in the eco-profile of forecasted Sicilian electricity generation mix characterized by a high renewable energy sources exploitation through a life cycle approach;
- to quantify the potential contribution of the future electricity generation mix in the achievement of the EU energy and climate targets.

The authors apply an attributional LCA approach according to the international standards of the ISO 14040 series [56,57]. The functional unit is the production of 1 kWh of gross electricity. The percentage composition of the electricity mix, per type of plant and energy sources in RS and in the two forecasted 2030 – BS and 2030 – DS is illustrated in Table 3.

The system boundaries include all stages of the electricity life cycle:

- raw materials and fuels supply;
- construction and plant operation;
- end-of-life disposal for hydroelectric, solar PV and wind power plants.

The Cumulative Energy Demand (CED) method is used to assess the global energy requirement (GER) of the FU [58]. The impact assessment was performed by means of the ILCD 2011 Midpoint method [59] in which the "Mineral, fossil & renewable resource depletion" impact category was substituted by the impact "Abiotic depletion" calculated only for mineral resources [60] (to avoid overlapping with the GER impact category). In addition, land use and water resource depletion impact categories re excluded from the analysis due to their high uncertainty [61].

The assessed energy and environmental impact categories are listed in Table 4.

Table 4. List of the energy and environmental impact categories

Impact category	Acronym
Global Energy Requirement	GER
Global warming potential (kg CO_{2eq})	GWP
Ozone depletion potential (kg CFC-11_{eq})	ODP
Human toxicity, non-cancer effects (CTUh)	HT-nce
Human toxicity, cancer effects (CTUh)	HT-ce
Particulate matter (kg $PM_{2.5eq}$)	PM
Ionizing radiation-human health (kBq $U^{235}{}_{eq}$)	IR-hh
Ionizing radiation-ecosystem (CTUe)	IR-e
Photochemical ozone formation (kg $NMVOC_{eq}$)	POFP
Acidification potential ($molH^{+}{}_{eq}$)	AP
Terrestrial eutrophication (mol N_{eq})	EU_T
Freshwater eutrophication (kg P_{eq})	EU_F
Marine eutrophication (kg N_{eq})	EU_M
Freshwater ecotoxicity (CTUe)	E_{FW}
Abiotic depletion - resource ($kgSb_{eq}$)	ADP_{res}

4.2 Life Cycle Inventory

Data collection is described in Section 3. The eco – profiles of electricity generation per type of plant and energy source are from the Ecoinvent database [62]. For the scenarios analysed the following assumptions are made:

- Since thermoelectric plants use mature technologies and have a lifetime up to 50 years, technological changes occurring over the next decades are assumed to be not significant [19]. Their energy and environmental impacts are assessed by using the eco – profile currently available.
- For onshore wind power plants and solar photovoltaic, eco-profiles improvement are expected in the near future thanks to more efficient material and technologies [63]. However, as the forecasts concern the short

- medium term, the authors assume that the LCI of current technology can model the technology that will be installed from today to 2030 with good approximation. Then, the assessment of the life cycle impacts associated to the future electricity production from photovoltaic and wind power plants is performed by using the LCI referred to the current technologies.

4.3 Life Cycle Impact Assessment and Interpretation

Table 5 shows the impacts on GER. Primary energy consumption decreases in both the forecasted electricity mixes compared to RS; with variation rates per kWh of electricity generated of -24.1% (2030 – BS) and -19.8% (2030 - DS). In particular, the renewable primary energy consumption increases in both scenarios, compared to the RS due to the increased share of renewable technologies in the forecasted electricity mix. Although the significant increase of the renewable primary energy consumption between 2014 and 2030 scenarios, the reduced share of non – renewable energy technologies causes an overall primary energy consumption reduction, since these technologies are characterized by a higher life cycle energy intensity compared to the renewable ones.

Table 5. GER in reference and in forecasted scenarios ($\text{MJ}_{\text{primary}}$/FU) (FU: 1 kWh of electricity)

GER	RS	2030 – BS (%)	2030 – DS (%)
Non-renewable ($\text{MJ}_{\text{primary}}$)	9.07E+00	-41.1	-33.7
Renewable ($\text{MJ}_{\text{primary}}$)	9.13E-01	144	118.7
Total ($\text{MJ}_{\text{primary}}$)	9.98E+00	-24.1	-19.8

The contribution of each power plant to the total GER is shown in Figure 3. Thermal power plants fuelled with natural gas, both power and CHP plants, are responsible for the highest contribution (more del 50%) in all the examined scenarios. This outcome reflects the percentage composition of the energy sources in the electricity mix production as natural gas accounts for about 45% in all the examined scenarios.

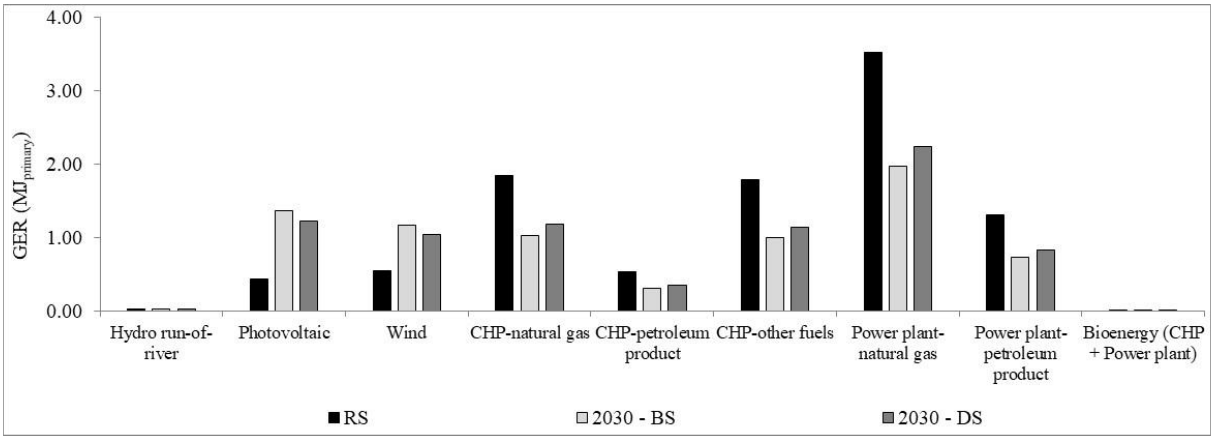

Figure 3. GER – process contribution.

The environmental life cycle impacts results are recapped in Table 6. The contribution of each power plant in the overall life cycle impacts is illustrated in Figure 4, Figure 5 and Figure 6 for each scenario.

The thermal plants (both power and CHP) fuelled with natural gas, although representing the 50% (for RS) to 30% (for 2030 – BS) of the whole electricity generation mix, are responsible for the highest impact only in three out of fifteen impact categories: GER, GWP and ODP. Regarding GWP, the high contribution is mainly due to the direct emission of CO_2 during the electricity production process. The impact on ODP is due to the long-distance transport of Russian natural gas[3]. This outcome highlights the importance of reducing the dependence on fossil fuels imports or, if possible, considering the geopolitical uncertainty in many producer regions, choosing the nearest supplier.

CHP-other fuel power plants represent a percentage of about 14% for RS and of about 8% for both 2030 – BS and 2030 – DS. Despite their contribution in the electricity mix being low, these plants are responsible for the larger contribution in three out of fifteen examined impact categories: HT – ce, HT – nce and EU_F.

Thermal power plants fuelled with petroleum product, that account for 13% of the total electricity generation for the RS and for about 7% for both 2030 – BS and 2030 – DS, are responsible for the larger impact in PM, IR – hh, IR – e, AC and EU_M. Specifically, the impact on PM, AC and EU_M is mainly related to the direct emissions occurring during the electricity production. Instead, the impact on IR impact categories is caused by the treatment of low radioactive level waste during the oil refinery process.

Concerning the renewable energy technologies, photovoltaic power plants are responsible for the larger impact on ADP_{res} in all the examined scenarios: around 64% in RS and 80% in 2030 – BS and 2030 – DS. The high contribution is mainly related to the mining and refining process of silver used in the production of the multi-Si wafer and to the extraction of zinc used in the mounting system of the PV panel. PV plants together with wind power plants are highly impacting in E_{FW}. Specifically, electricity from PV contributes for around 20% in RS and 40% in both 2030 scenarios. Electricity from wind power plants accounts for 20% in RS, and around 30% in both 2030 – BS and 2030 – DS. The process responsible for the highest contribution is the end-of-life treatment of copper used in the wind turbine and PV panel construction processes. This outcome highlights the need to reuse and/or recycle instead of disposing in order to improve the resource efficiency in a circular economy perspective [64] [65].

The thermal plants (both power and CHP) fuelled with bioenergy represent a significant contribution only in AP (around 17% in 2030 – BS and 14% in 2030 – DS) and EU_T (around 38% in 2030 – BS and 33% in 2030 – DS); the high contribution is mainly related to the direct emission during the storage and digestion anaerobic of the manure.

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[3] http://www.eniscuola.net/en/argomento/natural-gas1/extraction-and-distribution1/natural-gas-in-italy/

The hydropower run-of-river plants account for less than 0.1% in all examined impact categories and scenarios, respectively.

The improvement of the electricity eco-profile in the future scenarios has been assessed by the comparison with the eco-profile of the current electricity mix.

From data analysis results that all assessed scenarios involve a reduction of the impacts in all the examined environmental categories with the exception of E_{FW} and ADP_{res}.

A detailed analysis of the obtained results highlights that the impact on GWP and ODP decrease mainly as a consequence of the reduced electricity production from power plants fuelled with natural gas. In fact, these plants have a high specific contribution (per kWh) in these two impact categories.

HT – ce and HT – nce are the impact categories that show the lowest improvement. Specifically, compared to RS, they decrease by less than 10%, since these impact categories are highly affected by the photovoltaic and wind power plants. Concerning the photovoltaic power plant the impact in the HT categories can be related to the end-of-life treatment recognised highly impacting in HT – ce [61], while for the wind power plant it can be caused by the emissions of chromium to air during turbine manufacture [66].

Table 6. Life cycle environmental impacts related to the investigated scenarios per FU (1 kWh of electricity)

Impact category	RS	2030 - BS	2030 - DS
GWP (kg CO_{2eq})	6.48E-01	3.89E-01	4.35E-01
ODP (kg CFC-11_{eq})	8.25E-08	4.80E-08	5.42E-08
HT – nce (CTUh)	4.82E-08	4.48E-08	4.56E-08
HT – ce (CTUh)	1.44E-08	1.30E-08	1.33E-08
PM (kg $PM_{2.5eq}$)	2.27E-04	1.53E-04	1.66E-04
IR – hh (kBq U^{235}_{eq})	1.02E-02	7.39E-03	7.90E-03
IR - e (CTUe)	6.14E-08	4.00E-08	4.39E-08
POFP (kg $NMVOC_{eq}$)	1.48E-03	9.06E-04	1.01E-03
AP (molH^{+}_{eq})	3.87E-03	2.53E-03	2.74E-03
EU_T (mol N_{eq})	6.50E-03	4.85E-03	5.01E-03
EU_F (kg P_{eq})	8.02E-05	5.87E-05	6.27E-05
EU_M (kg N_{eq})	4.70E-04	2.93E-04	3.24E-04
E_{FW} (CTUe)	1.63E+00	2.18E+00	2.09E+00
ADP_{res} (kgSb_{eq})	2.77E-07	7.13E-07	6.43E-07

In the PM, POFP, AC, EU_T and EU_M impact categories the impact decreased of about 40% in 2030 – BS and 30% in 2030 – DS compared to RS. The improvement is mainly due to the reduced share of the production from thermal power plants fuelled with other fuels petroleum products.

In E_{FW} the impact increases of about 34% in the 2030 – BS and 28% in 2030 – DS. For this impact category, the decrease of the impact related to the reduced electricity generation from non – renewable energy technologies is totally offset by the increased impact of the electricity generated from photovoltaic and wind power plant.

The increase of the abiotic depletion potential in both scenarios is mainly due to the higher generation from photovoltaic power plants that involves a high consumption of materials in the manufacturing stage, e.g. silver that is highly impacting in this environmental category [60].

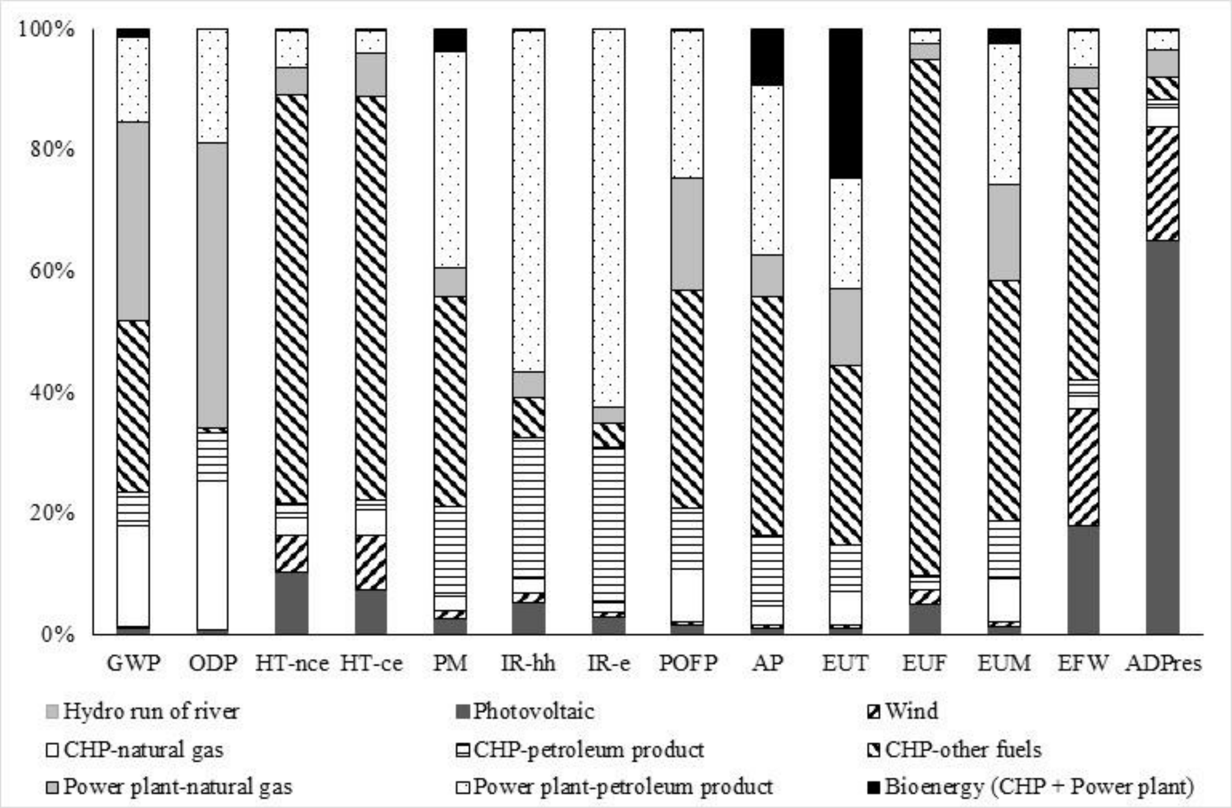

Figure 4. Environmental impact – process contribution in RS.

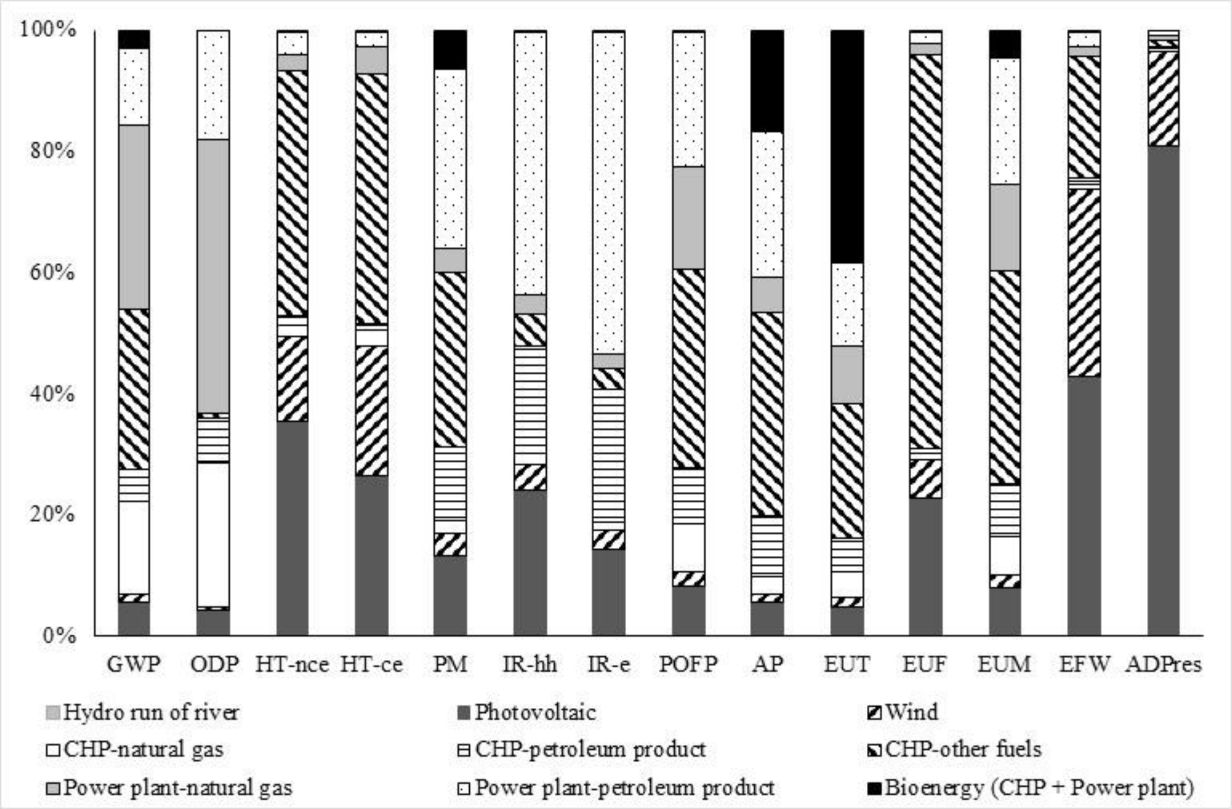

Figure 5. Environmental impact – process contribution in 2030 – BS.

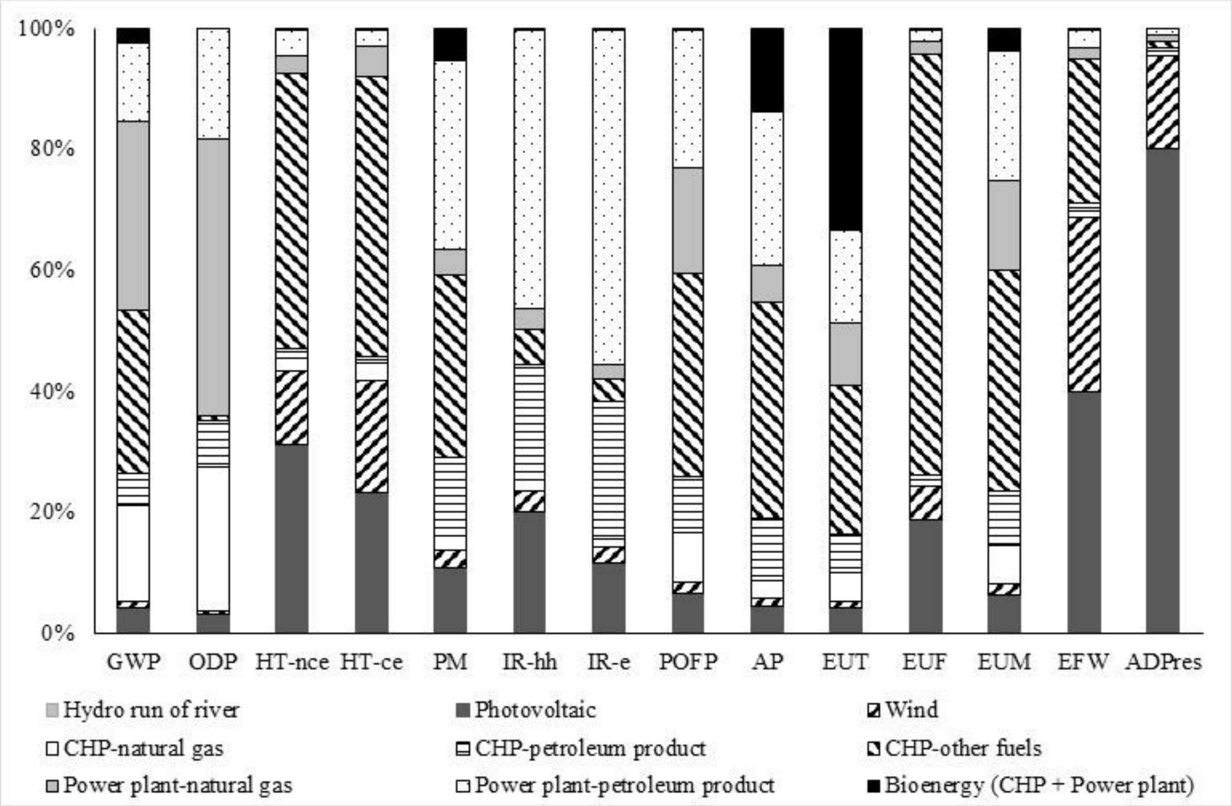

Figure 6. Environmental impact – process contribution in 2030 – DS.

5 Assessment of the potential contribution of Sicily in the achievement of the EU climate and energy targets

Both the future scenarios are in compliance with the EU energy strategy as they forecast a higher penetration of renewable energy sources reducing the energy dependence on fossil fuels. In detail, the share of renewable in the electricity generation mix is equal to 24% in RS, and increase up to 57% in 2030 – BS and to 51% in 2030 – DS.

The assessment of the potential contribution of the Sicilian electricity sector to the European energy and climate policy for 2030 is based on the forecasted electricity demand and the GWP per kWh of electricity generated in both the forecasted scenarios. The results are recapped in Table 7.

The assessment highlights that both the 2030 – BS and 2030 – DS scenarios can provide a positive contribution to the EU climate policy. This is an important outcome since actions at local level are necessary to match the global target on climate change. In addition, the analysis shows the importance to address the challenge of climate change with actions focused not only on the supply side but also on the demand side. In fact, the 2030 – DS scenario that foresees an increase of the electricity demand involve lower improvement in GHG emissions compared with the 2030 – BS scenario

Table 7. Global warming potential associated to the electricity production in reference and in forecasted scenarios

Scenarios	GWP ($kgCO_{2eq}/kWh$)	Electricity demand (GWh)	Global warming potential (tCO_{2eq})	Percentage variations
RS	6.48E-01	22,211	1.44E+07	
2030 - BS	3.89E-01	21,857	8.51E+06	-41%
2030 - DS	4.35E-01	24,441	1.06E+07	-26%

6 Conclusions

The implementation of low carbon strategies in the energy generation field requires the assessment of the energy and environmental implications connected with a high exploitation of renewable sources through a life-cycle approach.

In this study two energy generation mix scenarios for electricity generation in Sicily in 2030 are defined, in order to assess the potential contribution of the Sicilian electricity generation in the achievement of European energy saving and climate mitigation targets, and to estimate the potential environmental improvement of electricity mixes characterized by a higher penetration of renewable sources considering a wide range of environmental categories. For these purposes the LCA methodology is integrated with the scenario analysis.

The outcomes show that the forecasted scenarios, if accomplished, would involve a reduction of the primary energy consumption in both 2030 scenarios compared to the current one as a consequence of high penetration of renewable electricity generation technologies characterized by a lower energy intensity compared to the fossil fuels ones. In addition, both the foreseen scenarios propose a reduction in GHG emissions per kWh of electricity generated. The assessed scenarios would involve an overall reduction in almost all other environmental impact categories. However, the analysis of a wide range of environmental aspects of sustainability through the multi – indicator approach of LCA highlights that, with the current state of development of electricity technologies generation, it is not possible to achieve improvements in a whole set of environmental impacts categories. Specifically, both 2030 scenarios involve an increase of the impacts on freshwater ecotoxicity and abiotic depletion in which electricity from renewable technologies (mainly PV systems and wind turbines) is highly impacting.

Thus, the results highlight the importance of integrating the LCA methodology in the design process (eco-design) in order to improve the PV and wind systems in terms of resources efficiency and toxicity control. In addition, it is paramount to guarantee easy disassembly of the electricity generation technologies in order to encourage the use of circular economy strategies aimed at reusing and recycling the raw material instead of disposing them, avoiding the production of primary materials and the disposal of potential hazardous substances.

In order to achieve a more sustainable economy it is paramount to provide policy makers with scientific based knowledge on the wide dimension of the environmental sustainability, since focusing on one environmental aspect could cause a worsening of other environmental problems. In this context, the LCA integrated with a consistent scenario analysis has proved to be one of the most suitable methodologies.

With reference to climate change, the study shows that the Sicilian electricity sector can contribute to the European climate policy for 2030. Although the estimates amount account for a small percentage of the overall EU GHG emissions, they represent a significant contribution in the achievement of the overall goal, as effects of actions at local scale. Moreover, the study confirms that in order to achieve the EU climate goal, coupling strategies aimed at promoting the renewables with strategies aimed at increasing the energy efficiency and reducing the energy consumption through the consumers' empowerment is crucial. The study shows that if the strategies aimed at increasing the renewable sources share in the energy mix are non-integrated with actions aimed at increasing the energy efficiency and changing the consumers 'behaviours, the benefits could be less than expected.

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