Life-cycle assessment applied to future scenarios of electricity generation in Sicily

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Abstract

Fighting global warming and increasing the energy security are some of the most relevant objectives of the European energy policy. Thus, defining potential low carbon pathways for the energy sector is of paramount importance in order to identify strategies with the lowest impact on climate.

This paper deals with the energy and environmental assessment of future electricity scenarios in Sicily (Italy), for 2030, characterized by a high exploitation of renewable energy sources, with the aim to quantify the potential contribution of the Sicilian electricity mix in the achievement of the European energy and environmental goals and to evaluate the achievable potential improvement in the future electricity mix, compared to the current one (2014).

In order to match these goals, the authors integrate the Life Cycle Assessment methodology, according to the standard of the ISO 14040 series, with the scenario analysis.

Both the forecasted electricity mix scenarios, characterized by a share of renewables equal to 36% and 32%, show a reduction of the global energy requirement and correspondent GHG emissions per kWh of electricity generated, compared to the current one in which renewables account for 24%. However, the analysis of a wide range of environmental categories highlights that with the current state of development of electricity technologies generation is not possible to achieve improvements in a whole set of environmental impacts categories.

Data and results of this study are site – specific and updated on current and on future Sicily electricity mix generation that can be used as knowledge base in the definition of low carbon energy strategies in Sicily. Moreover, they can support the decision makers and the local authorities in an "ex ante" evaluation of the energy and climate strategies aimed at reducing the greenhouse gases emission.

Keyword

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

1 Introduction

The need of a decarbonized, resource-efficient and biodiverse economy for fighting climate change and the loss of ecosystems and biodiversity (European Commission, 2019) 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 environment degradation from the improvement of health, welfare and well-being (European Commission, 2019). The EU is in fact already taking actions to curb GHG emissions in all areas of its activity. 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 (European Commission, 2017, 2007), which is responsible of roughly two-thirds of all anthropogenic greenhouse-gas (GHG) emissions (IEA - International Energy Agency, 2015).

The clean energy transition would result in an energy system where primary energy supply would largely come from renewable energy sources (European Commission, 2018) and as a milestone towards this goal, the use of renewable energy sources is expected to achieve a share of at least 27% of European energy consumption within 2030 (European Commision, 2014).

Focusing on the energy use, by 2050 the share of electricity in final energy demand will at least double, bringing it up to 53%, and more than 80% of electricity will be coming from renewable energy sources (RES) (increasingly located off-shore) (European Commission, 2018).

The decarbonization of electricity is a key component of mitigation strategies aimed at stabilizing the levels of carbon dioxide concentration in the atmosphere in most integrated future effects of climate change modelling (IPCC, 2014), and it is one of the means towards several of the objectives presented by Sustainable Development Solutions Network (SDSN) in “An Action Agenda for Sustainable Development” (United Nations, 2014). 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 (International Energy Agency, 2014).

However, in order to achieve the ambitious objectives of decarbonization of the economy, it is needed 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.

In this context, 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 mix (Beccali et al., 2007). These benefits have to be evaluated following a life-cycle approach, taking into account a wider perspective than the mere use stage.

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

The authors applied the Life Cycle Assessment (LCA) methodology, as it allows for evaluating the energy and environmental impacts connected to the whole life cycle of the electricity generation and its indirect impacts (Cellura et al., 2018). The improvement of the electricity eco-profile in the future scenarios has been assessed by the comparison with 2014 data, assumed as reference year, as it represented the year with a more detailed available data on electricity generation among the most recent data available.

The paper includes the following original contributions:

- It is one of the first applications of the LCA methodology combined with a scenario analysis in the Italian context, aimed at quantifying the sustainability of future electricity generation scenarios at regional scale and its contribution on the achievement of the EU energy and environmental goals.
- It represents a medium-term, regional scale analysis of electricity generation scenarios that can support national and local decision makers in the definition and evaluation of low-carbon energy strategies.

Data and results of this study represent site-specific eco-profiles of current and potential future electricity mixes defined taking into account the needs and the peculiarities of the local context. 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 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 2030 European Union climate and energy targets. Section 6 provides some final remark.

2 Literature review

Several studies are available in literature assessing the environmental burdens due to electricity generation in future forecasted scenarios through a life – cycle approach.

Treyer and Bauer (Treyer and Bauer, 2016) defined four scenarios of energy mixes for the electricity generation in the United Arab Emirates in 2020, 2030 and 2050 with the aim to estimate the trends in environmental impacts according to different supply mixes. The authors applied the LCA methodology according to the standards ISO 14040 and ISO 14044 (ISO, 2006a, 2006b). Future scenarios were built considering: growing population and energy demand; existing or near-future treaties and energy goals; geographical constraints and conditions; interlink between the water and electricity sectors; lifetime of power plants and desalination plants. The resulting scenarios were:

1) "Planned action" scenario, which took into account the current policy measures and regulations in force in each Emirate (7% renewable electricity by 2020 in Abu Dhabi, 5% renewable electricity in Dubai by 2030, and four nuclear power plants until 2020);

2) "Planned action with carbon capture storage (CCS)", which considered that after 2030 all new natural gas plants will be equipped with CCS;

3) "Nuclear scenario", which foresaw the installation of nuclear power plants (4 nuclear power plants in 2020, 6 in 2030 and 8 in 2050);

4) "Renewables scenario", which considered the introduction of a high share of renewable energy sources (7% in 2020, 15% in 2030 and 30% in 2050), compared to the 2010 electricity mix scenario, where natural gas has a share of 98.3%.

The study showed that all future scenarios involved a reduction in climate change, particulate matter, terrestrial acidification and human toxicity. Instead, "Renewable scenario" showed an increase in Terrestrial, Freshwater and Marine Ecotoxicity and in metal depletion, mostly due to wind and PV plants installation.

Stamford and Azapagic (Stamford and Azapagic, 2014) applied a life cycle sustainability assessment to quantify the energy and environmental performances of different electricity generation scenarios in the United Kingdom from 2009 to 2070. The scenarios were driven by the need to reduce GHG emissions and were defined considering the electricity generation technologies which were expected to play a major role in the future UK electricity mix (UK Government, 2011). The authors considered five scenarios characterized by different percentage reductions in GHG emissions for electricity production in 2050 relative to 1990. Two of them involved a reduction of 65%. In the first scenario, it was assumed that the CCS technology would become economically available and that it would be implemented in coal thermal plants. The second one included the use of CCS and the construction of new nuclear plants. One scenario involved a reduction of 80% of GHG. It considered the construction of new nuclear power plant and some coal CCS. Finally, two scenarios portrayed a fully decarbonized energy sector. In the first one the electricity was generated by solar PV and offshore wind. In the second one, the authors took into account the construction of new nuclear power plants and a major exploitation of renewable sources. The study showed that, in all scenarios analysed, increasing the penetration of nuclear and/or renewable energy exploitation involved a reduction of environmental impacts arisen from the electricity generation, except for terrestrial ecotoxicity and land use.

Turconi et al. (Turconi et al., 2014) performed a consequential LCA to assess the environmental impacts of a 2030 low-carbon electricity system (2030 – Green scenario) in Denmark, compared with the current scenario (year 2010) and with a business as usual 2030 scenario (2030 – BaU scenario). The 2030 – Green scenario was defined in compliance with targets set by the European Union and the Danish government and was characterized by a high wind penetration and a substitution of fossil fuels with biomass. The development of the wind sector was based on economic projections and forecasts from the Danish Energy Agency, while regarding the biomass, it was assumed that the amount required in the electricity system was covered partly by available domestic resources and partly by import of wood from other countries. The two future scenarios for the Danish electricity system were defined by taking into account the expected electricity demand growth (including electrification of heat and of transport sectors), the dismantling of existing power plants, and the development of technologies used for power generation and including import/export of electricity. From the study resulted that the goals to reduce GHG emissions and fossil fuel dependency could be achieved, as the 2030-Green scenario reported a significant reduction in GWP and Fossil Resource Depletion, compared to the current and the 2030 – BaU scenarios. This reduction was essentially due, in both scenarios, to wind energy increase and the substitution of fossil fuel (in particular coal and natural gas) with biomass. Besides GWP and fossil resource depletion, the impacts on marine eutrophication, terrestrial acidification and terrestrial ecotoxicity categories showed a significant reduction. Conversely the Abiotic Resource Depletion impact increased in both scenarios due to metals consumption in the construction of wind turbines.

Dandres et al. (Dandres et al., 2012) presented a new LCA approach which combined elements of prospective LCA and economic modelling to evaluate the direct and indirect environmental impacts arisen from heat and electricity generation scenarios in the EU between 2005 and 2025. They considered two EU energy scenarios: the “baseline scenario", which was a BaU scenario, where energy policies set in 2000 were extended to 2025; and the "bioenergy scenario", based on a significant increase (from 2 Mtoe to 22 Mtoe) in biomass utilization and a reduction of EU demand for coal. Both scenarios were generated using a partial equilibrium economic model designed to predict the evolution of European energy markets based on the changes in prices, demand and supply in each European country. The direct impacts of electricity and heat generation were assessed through the P – LCA to include technological evolution during the period. The economic effects related to both scenarios were modelled using the GTAP economic model, a multi - region, multi - sector, computable general equilibrium model (Hertel Thomas W., 1997), and the results were used to assess the indirect impacts. This study showed that the bioenergy scenario involved the lowest impacts with regard to human health, GWP, and natural resource consumption, but the most significant impact for Ecosystem.

Felix and Gheewala (Felix and Gheewala, 2012) applied a life cycle approach to assess the environmental impacts driven by the centralized grid-connected electricity generation in Tanzania in 2000, 2015, 2020, 2026 and 2030. The future electricity scenarios were defined according to the Tanzania Electricity Supply Company's plans for power system expansion. The electricity was generated from hydropower and fossil-based fuel sources, both in the current and future scenarios. Due to the increase of fossil fuel generation in the local energy mix from 11% to 58%, all of the environmental impacts grew from 2000 to 2030. In detail, the following environmental impact categories were assessed: abiotic resource depletion, eutrophication potential, climate change, and acidification potential.

The above studies highlight that the most significant energy and environmental improvement of the electricity eco-profile could be achieved replacing fossil fuels with renewable energy sources in electricity generation systems. However, it is not possible to achieve improvements in the whole set of environmental impacts indicators (Cellura et al., 2015b). Some LCA studies of energy technologies suggest that, per unit generation and in some specific contexts, low-carbon power plants may require more raw materials than fossil-fuelled plants involving in some cases the increase of some impact categories (Hertwich et al., 2015). In this framework, also the availability of site-specific data on electricity generation it is of paramount importance. In fact, as highlighted by Cellura et al. (Cellura et al., 2018), the use of site - specific electricity mix can entail a reduction of the GHG emissions of about 7% if compared to those calculated using an average national electricity mix. Then, they allow for obtaining a more reliable evaluation of the climate strategy in sectors that involve electricity consumption (e.g. energy related products (Cellura et al., 2014; European Council, 2009) or buildings (Cellura et al., 2015a)).

The LCA combined with scenario analysis based on realistic forecast provides scientific based environmental evaluation of the implemented strategies and can represent a useful methodology for the EU Member States in order to match the EU climate goals avoiding the potential shifts of impacts to other crucial environmental categories, like resource depletion or human toxicity. The results can support the EU decision makers in the continuous improvement of the climate policies for Member States. In this context, the presented study can represent a useful example implemented at regional scale, in which all investigated scenarios are defined considering both the Italian contribution to the EU climate targets and the potential available exploitation of renewable energy sources.

3 Electricity generation scenarios

This section describes the steps followed for the definition of 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 illustrated in Figure 1.

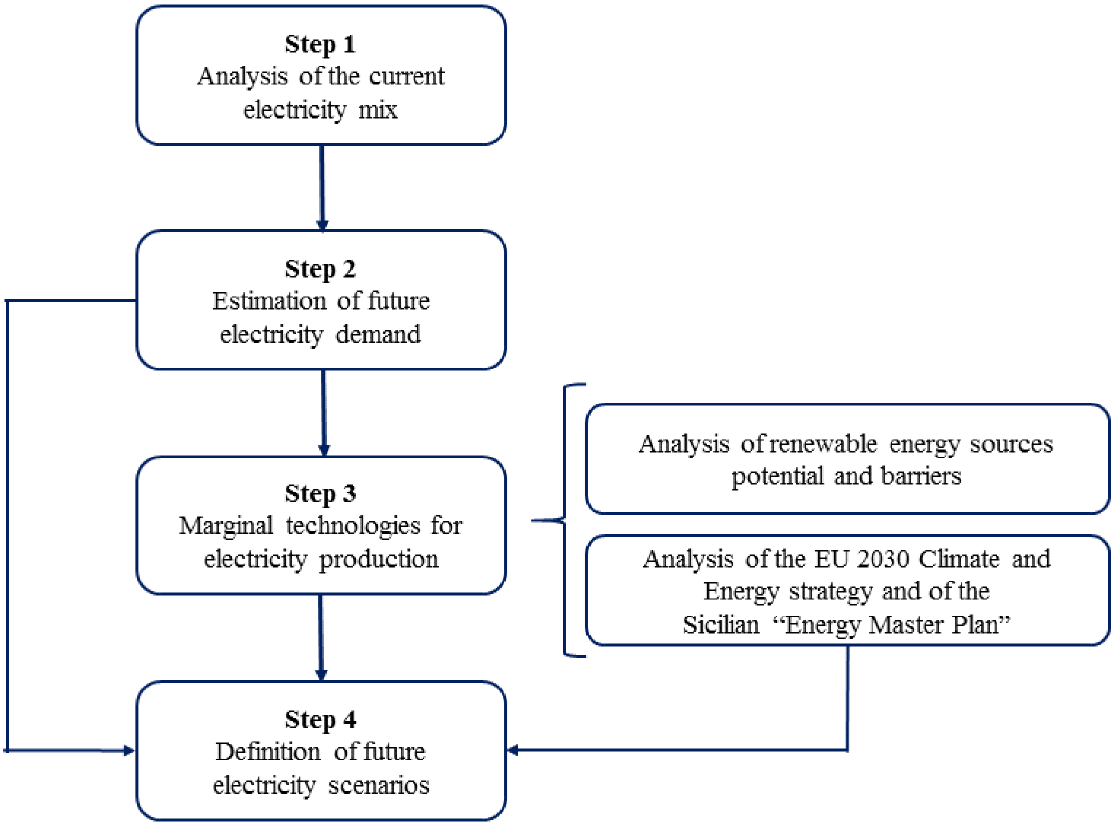

Figure 1. Steps for the definition of electricity generation scenarios.

- 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 – Marginal technologies for electricity production. The selection of the energy marginal technologies was based on 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 were merged to define electricity mix scenarios in compliance with the European Union climate and energy policies.

In the following paragraphs 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 employed in Sicily for the electricity generation have been collected with the aim to depict the Sicilian current electricity mix and to assess the current level of renewable exploitation in the island. Data were mainly obtained from two sources: the grid operator for electricity transmission in Europe (TERNA group), which publishes statistics on electricity generation in the various Italian Regions (TERNA, 2017a), 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 (GSE, 2017).

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 (Region of Sicily, 2015).

Table 1 shows the gross electricity generation in Sicily from 2009 to 2014 disaggregated by technology and energy source, with the exception of the electricity generation in pumped storage units from water previously pumped uphill (European Union, 2009). Updated data until 2017 from TERNA and GSE are available. However, disaggregated data on the thermal power plant were only available until 2014.

Thus, the electricity mix in 2014 was assumed as reference (Reference Scenario - RS). In this year, the total installed power was 9,463.7 MW (60% thermal power plants, 18.6% wind, 13.7% of solar PV and 7.7% hydro power) (TERNA, 2017a).

The analysis of the data from 2009 to 2014 showed a progressively evolution 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 was mostly based on thermal power plants fuelled by fossil sources, which accounted for more than 70% of the whole production in the RS. The share of natural gas was 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 more than tripled between 2009 and 2014, and it accounted for around 24% of the total electricity production 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 (TERNA, 2017a) (GSE, 2017)).

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 future electricity demand was based on TERNA (TERNA, 2017b), which proposes two possible scenarios for future electricity demand in Sicily. The first one, designated as "Base scenario" (BS), which is based on an estimated gross domestic product growth of 0.9%, estimated a decrease of the electricity demand with an average annual rate of 0.1%; the second one, designated as "Development scenario" (DS), which is based on an estimated gross domestic product growth of 1.3%, reported an increase of the electricity demand with an average annual rate of 0.6%.

The authors depicted two possible evolutions for electricity demand in Sicily, one assuming the BS hypothesis and the other one assuming the DS hypothesis. The obtained electricity estimates for 2030 were:

- 21,857.3 GWh in BS;
- 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 defined as a technology able to adjust the production or the production capacity to meet the changes in demand (Weidema et al., 1999). Specifically, a marginal electricity technology is defined as a technology that will change its production in response to a change in demand in an energy system (increase or decrease). Marginal technologies are unconstrained technologies, i.e. their capacity can be adjusted in response to a change in demand (Weidema et al., 1999) without being subjected to natural capacity (e.g. availability of land for energy crop production) or political constraints (e.g. GHG emission limits). 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 (Muñoz, 2015).

The selection of the renewable energy marginal technologies was performed considering three main 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. limitations) (Lopez et al., 2012).

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% (European Commision, 2014). 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. Then, the short – medium marginal electricity production technologies should be renewable energy technologies.

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

In the following paragraphs, the potential impact of each technology and the barriers to their diffusion are described more in detail within the context of the Sicilian framework, under the assumptions discussed previously. The evaluation was based on national and regional reports (Benini et al., 2010) (Region of Sicily, 2008).

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.), to the impacts on the eco-system (Mattmann et al., 2016) and the need to consider other water – using sectors (e.g. agriculture, domestic and industrial uses) (Loucks and van Beek, 2017) (IEA - International Energy Agency, 2012) (IEA - International Energy Agency, 2010). In the Sicilian "Energy Master Plan" (Region of Sicily, 2008), the official document in which the current energy sector and the energy strategies for the short – medium period are illustrated, the forecasted 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 (Cattini et al., 2011; Region of Sicily, 2008).

From the abovementioned 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 (IEA - International Energy Agency, 2013) (IEA - International Energy Agency, 2008). The potential for exploitation of wind resource in Sicily was based on three Italian studies (ANEV, 2018), (Benini et al., 2010) (Alterach et al., 2011).

Benini et al. (Benini et al., 2010) and Alterach et al. (Alterach et al., 2011) 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. (Benini et al., 2010) and to 3.51 TWh in Alterach et al. (Alterach et al., 2011), marking a variation of 30% and 20% to the wind generation in 2014, respectively. More updated data were inferred from ANEV (ANEV, 2018) that 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./a.s.l. of 2000 MWh/MW (RSE, 2018) (Figure 2), an electricity generation of 4000 GWh corresponds to the 2000 MW of installed power.

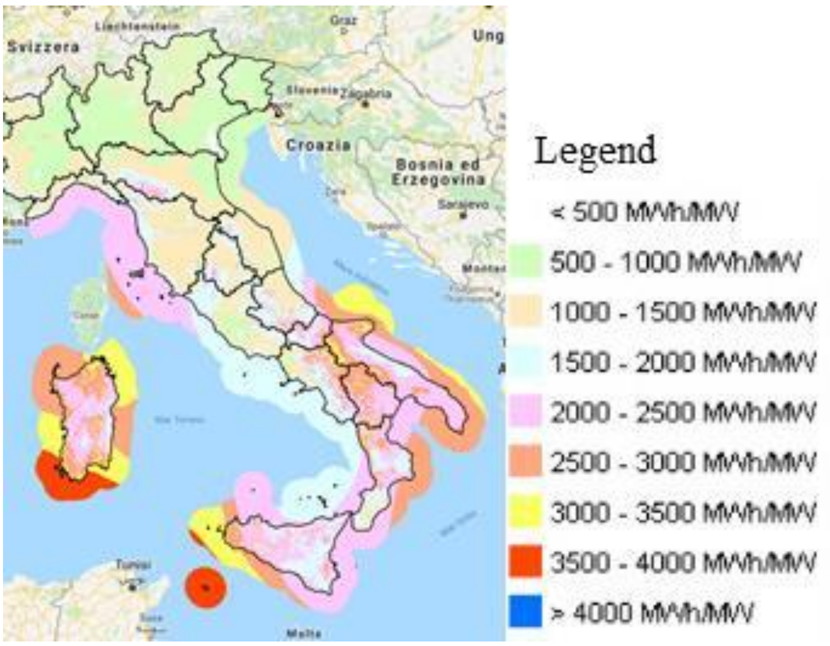

Figure 2. Specific annual energy production at 75 m a.t.l./a.s.l. (RSE, 2018).

Because of the installed power was 1700 MW, in 2014 wind power plants were considered energy marginal technologies for the Sicilian electricity sector.

With regard to offshore wind power plants, due to the significant impact of these infrastructures on the main activity of the Sicilian economy, such as fishing, tourism and bathing areas (Region of Sicily, 2015), the authors assumed that they cannot be considered electricity marginal technologies in the Sicilian context in the short – medium period.

Solar photovoltaic. The penetration of this technology depends on the cost (and the related incentives), and the acceptability of the impacts (e.g. visual) involved mainly in the case of ground mounted systems.

In Sicily the potential contribution of solar energy estimated in the "Energy Master Plan" (Region of Sicily, 2008) is very high. In detail, with regard to building integrated photovoltaic systems, it is about 37 million m^2.

The global installed solar power capacity in Sicily was 1294.9 MW in 2014, while an installable capacity equal to 1812 MW is forecasted for 2020 (Region of Sicily, 2014). Since forecasts for 2030 were not available, the estimation made for 2020 was assumed to has a conservative assumption for 2030. An average photovoltaic power plant productivity of 1600 MWh/MW (Figure 3) can be assumed for Sicily (EC - JRC, 2017), resulting in a potential electricity generation of 2900 GWh.

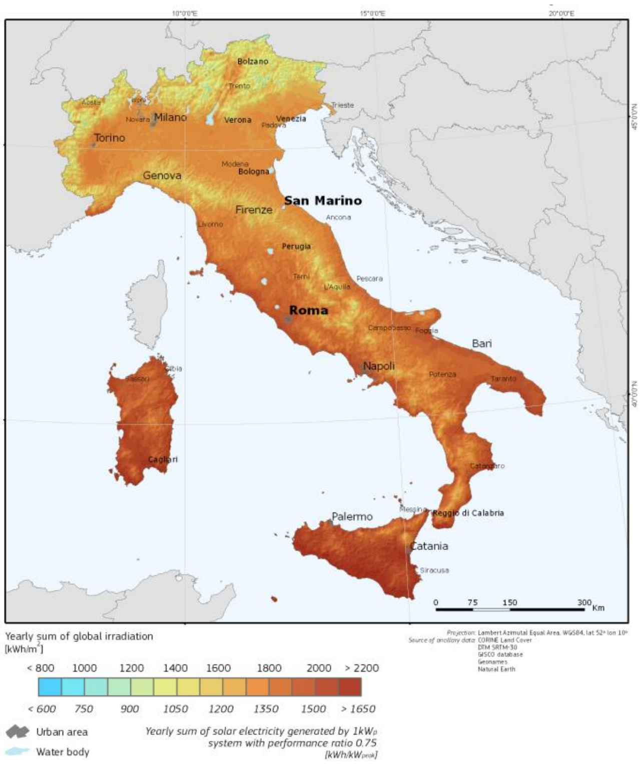

Figure 3. Yearly sum of solar electricity generated by 1 kWp system (EC - JRC, 2017).

The solar photovoltaic technology is considered a marginal technology, as within the renewable technology sector, solar power seems to be the most promising, considering the Sicily high solar irradiation (Huld et al., 2012; Šúri et al., 2007) and the unrealized potential discussed in the Sicilian Energy Master Plan (Region of Sicily, 2014, 2008).

Bioenergy. Main barriers to bioenergy thermal plants are costs, conversion efficiency, transportation cost, feedstock availability, lack of logistics supply and the competition with the bioenergy uses for heat generation and transport (IEA - International Energy Agency, 2007).

The electricity production in Sicily from bioenergy was 259.2 GWh in 2014. Benini et al. (Benini et al., 2010) estimated that the potential electricity generation from thermal plants fuelled with bioenergy in Sicily in 2020 will increase up to 795 GWh. The study takes into account several potential uses of bioenergy as energy source and other purposes, such agricultural applications. In addition, the Sicily 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 (Region of Sicily, 2008). On these bases, thermal plants fuelled with bioenergy were considered a marginal technology for the Sicilian energy sector. As forecasts for 2030 were not available and considering that the electricity production from thermal plant fuelled with bioenergy in RS (259 GWh) was still far from the forecasted potential, the estimates for 2020 were assumed for 2030.

3.4 Step 4: Future electricity scenarios definition

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

Two scenarios, defined as 2030-BS and 2030-DS, were 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. The amount of electricity generated from hydropower in 2030 was 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 2. Level of exploitation of the renewable energy sources forecasted for 2030.

Marginal electricity technology	Estimated production in 2030 (GWh)	Estimated increase compared to RS (%)
Photovoltaic	2900	36.9
Wind	4000	53.2
Bioenergy	795	206.9

Table 3 illustrates 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	13.3	11.9
Wind	13.2	18.3	16.4
CHP* -natural gas	21.5	18.0	19.1
CHP - oil products	4.1	3.4	3.6
CHP -other fuels (solid)**	14.9	12.5	13.3
Power plants - natural gas	27.5	23.1	24.4
Power plants - oil products	8.4	7.1	7.5
Bioenergy*** (CHP + Power plants)	1.2	3.6	3.3

*CHP: combined heat and power plant.
**Other solid fuels: brown coal briquettes, coke, etc.
***Bioenergy: biogas, biomass and bioliquid.

It is worth mentioning that the scenarios were developed while taking in consideration the sustainability of the choices modelled, and their impacts on the structure of the electricity distribution system, even under conditions of high penetration of renewable energy sources.

The technical potential assumed in this paper is sustainable for the actual Sicilian electricity grid capacity (Alterach et al., 2011; Benini et al., 2010). Scenarios with higher penetration of renewable energy sources will require a further expansion of the grid capabilities and the implementation of energy storage technologies on a local scale (Guarino et al., 2015; Longo et al., 2014) (Cusenza et al., 2019) able to manage the variability in renewable energy sources output and to guarantee a more stable electricity system.

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 mix production characterized by a high renewable energy sources exploitation through a life cycle approach;
- to quantify the potential contribution of the forecasted electricity mix in the achievement of the EU energy and climate targets.

The authors applied an attributional LCA approach according to the international standards of series ISO 14040 (ISO, 2006a, 2006b). The selected functional unit was 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.

For thermal power plants the end-of-life is not considered due to the lack of secondary data.

The Cumulative Energy Demand (CED) method was used to assess the global energy requirement (GER) of the FU (Frischknecht et al., 2007). The impact assessment was performed by means of the ILCD 2011 Midpoint method (European Commission and Joint Research Centre, 2012) in which the "Mineral, fossil & renewable resource depletion" impact category was substituted by the impacts "Abiotic depletion" calculated only for mineral resources (Van Oers et al., 2002)(to avoid overlapping with the GER impact category). In addition, land use and water resource depletion impact categories were excluded from the analysis due to their high uncertainty (Latunussa et al., 2016).

The assessed energy and environmental impact categories are:

- Global energy requirement (GER);
- Global warming potential (GWP);
- Ozone depletion potential (ODP);
- Human toxicity, non-cancer effects (HT-nce);
- Human toxicity, cancer effects (HT-ce);
- Ionizing radiation-human health (IR-hh);
- Ionizing radiation-ecosystem (IR-e);
- Photochemical ozone formation (POFP);
- Acidification potential (AP);
- Terrestrial eutrophication (EU_T);
- Freshwater eutrophication (EU_F);
- Marine eutrophication (EU_M);
- Freshwater ecotoxicity (E_{FW});
- Abiotic depletion - resources (ADP_{res}).

4.2 Life Cycle Inventory

The 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 (Wernet et al., 2016). 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 not significant (Stamford and Azapagic, 2014) and then, the energy and environmental impacts were 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 (European Commission -- Joint Research Centre -- Institute for Environment and Sustainability, 2014). However, due to the uncertainty in technological development and in life cycle data for future technologies (Stamford and Azapagic, 2014), assuming a cautious scenario, the future eco – profiles improvement of both photovoltaic and wind technologies is neglected.

4.3 Life Cycle Impact Assessment and Interpretation

Table 4 illustrates the impacts on global energy requirement category in the investigated scenarios. Primary energy consumption decreases in both the forecasted electricity mix compared to RS, the percentage variations per kWh of electricity generated are -9.6% (2030 – BS) and -6.8% (2030 - DS). 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. The decrease of the non – renewable primary energy, due to the reduced share of non – renewable energy technologies, results in an overall primary energy consumption reduction since these technologies are characterized by a higher life cycle energy intensity compared to the renewable ones.

Table 4. Global energy requirement in reference and in forecasted scenarios ($MJ_{primary}$/FU) (FU: 1 kWh of electricity)

Global energy requirement	RS	2030 – BS (%)	2030 – DS (%)
Non-renewable ($MJ_{primary}$)	8.74E+00	-15.1	-10.4
Renewable ($MJ_{primary}$)	9.31E-01	41.8	27.5
Total ($MJ_{primary}$)	9.67E+00	-9.6	-6.8

The contribution of each power plant to the total global energy requirement is detailed in Figure 4. Thermal power plants fuelled with natural gas, both power and CHP plants, are responsible for the highest contribution to the energy impact in RS and in both the forecasted scenarios. In detail, they account for more than 50% of the overall primary energy consumption in all the investigated 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.

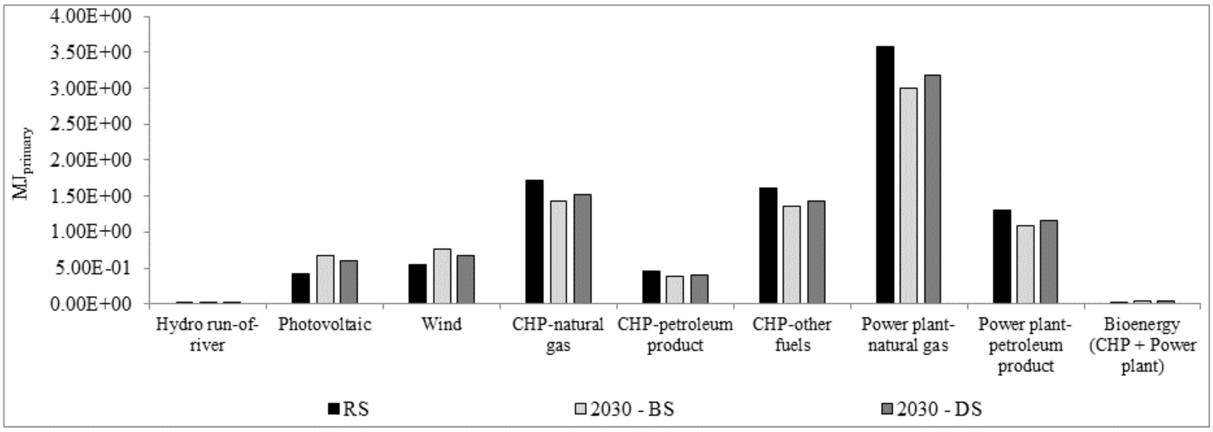

Figure 4. Global energy requirement – process contribution.

The environmental life cycle impacts results are illustrated in Table 5. The contribution of each power plant in the overall life cycle impacts is illustrated in Figure 5 for RS, in Figure 6 and Figure 7 for the 2030 – BS and 2030 – DS, respectively.

The thermal plants (both power and CHP) fuelled with natural gas, although represent a share in the investigated electricity mix ranging from 50% (for RS) to 41% (for 2030 – BS) are responsible for the highest impact only in three out of fifteen examined impact categories: global energy requirement, global warming and ozone depletion potential. CHP-other fuel power plants represent a percentage of about 14% in the examined electricity mix and they are responsible for the larger contribution in three out of fifteen examined impact categories: human toxicity cancer and non-cancer effect and freshwater eutrophication. Thermal power plants fuelled with petroleum product, that account for 11% of the total electricity generation, are responsible for the larger impact in particulate matter, ionizing radiation – human health and ecosystem and marine eutrophication.

Concerning the renewable energy technologies, photovoltaic power plant is responsible for the larger impact in abiotic depletion potential in all the examined scenarios: 64% in RS, 70% in 2030 – BS and 2030 – DS; electricity from wind power plants is highly impacting in freshwater ecotoxicity in which account for 34% in RS, for 40% in 2030 – BS and 37% in 2030 – DS. The thermal plants (both power and CHP) fuelled with bioenergy and hydropower run-of-river plants account for less than 5.0% and 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 freshwater ecotoxicity and abiotic depletion potential.

A detailed analysis of the obtained results highlights that the impact on global warming potential and ozone depletion potential 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: in RS, they account for around 35% of global warming potential and 47% of ozone depletion potential (Figure 5).

In 2030 – BS and 2030 – DS, thermal power plants fuelled with natural gas remain the larger contributors to global warming potential and to ozone depletion potential. In detail, they represent about 33% of the total impact on global warming potential and 46% of the ozone depletion potential in all the examined scenarios. They contribute for a percentage of 36% and 48% of the global warming potential and ozone depletion potential reduction, respectively.

The above environmental benefits are partially offset by the higher penetration of renewable energy sources. Specifically, in global warming potential, the increased impact related to the renewables offset the achievable improvement of about 8%, and the thermal power plant fuelled with bioenergy are responsible for the highest contribution. In ozone depletion potential, the increased production from renewable energy sources reduces the achievable improvement of about 3% due mainly to the increased share of electricity generated from photovoltaic power plant.

In global warming potential significant contribution are also due to the electricity produced from CHP plants fuelled with other fuels that accounts for about 25% in all the investigated scenarios, while in ozone depletion potential the electricity produced from CHP natural gas and power plant fuelled with oil products account, respectively, for around 22.4% and 21%.

Human toxicity – non cancer and cancer effect are the impact categories that show the lowest improvement. Specifically, compared to RS, human toxicity – non cancer effect decreases by 2.3% in 2030 – BS and 1.5% in 2030 – DS; human toxicity – cancer effect by 2.5% in 2030 – BS and by 2% in 2030 – DS. The increased share of electricity form photovoltaic and wind power plants reduces the potential improvement in human toxicity non-cancer of 45% in the 2030 – BS and of 38% in the 2030 – DS; while in human toxicity – cancer effect of 47% in the 2030 – BS and of 40% in the 2030 – DS. Concerning the photovoltaic power plant the impact in the human toxicity categories can be related to the end-of-life treatment recognised highly impacting in human toxicity – cancer effect (Latunussa et al., 2016), while for the wind power plant it can be caused by the emissions of chromium to air during turbine manufacture (Greening and Azapagic, 2013).

The reduced electricity generation from cogeneration plants fuelled with other fuels is responsible for the larger eco-profile improvement in human toxicity – non cancer effect and cancer effect and freshwater eutrophication. Specifically, they contribute for 60% and 75% on the impact reduction in human toxicity categories and freshwater eutrophication, respectively.

In ionizing radiation – human health and ecosystem and in particulate matter impact categories power plant fuelled with petroleum product are responsible for the highest impacts in all the investigated scenarios. The impacts in these environmental categories decrease by 12.5% in the 2030 – BS and by 8.5% in the 2030 – DS compared to RS. The impact decrease is mainly related to the reduced electricity generated from power plants fuelled with petroleum product, and the achievable environmental improvement is mainly offset by the higher share of electricity from photovoltaic power plant.

The CHP power plants fuelled with others fuel are responsible for the highest impacts on photochemical ozone formation, acidification potential, terrestrial, freshwater and marine eutrophication impact categories. In the 2030 – BS the impacts decrease of about 14%, while in the 2030 – DS of about 9% compared to RS.

Table 5. Life cycle environmental impacts related to the investigated scenarios per FU (1 kWh of electricity)

Impact category	RS	2030 - BS	2030 - DS
Global warming potential (kg CO_{2eq})	6.23E-01	5.48E-01	5.74E-01
Ozone depletion potential (kg CFC-11_{eq})	7.42E-08	6.31E-08	6.65E-08
Human toxicity, non-cancer effects (CTUh)	3.97E-08	3.88E-08	3.91E-08
Human toxicity, cancer effects (CTUh)	1.16E-08	1.13E-08	1.14E-08
Particulate matter (kg $PM_{2.5eq}$)	2.25E-04	1.97E-04	2.06E-04
Ionizing radiation-human health (kBq $U^{235}{}_{eq}$)	1.55E-02	1.37E-02	1.43E-02
Ionizing radiation-ecosystem (CTUe)	7.88E-08	6.82E-08	7.15E-08
Photochemical ozone formation (kg $NMVOC_{eq}$)	1.33E-03	1.14E-03	1.20E-03
Acidification potential (mol$H^{+}{}_{eq}$)	3.34E-03	2.87E-03	3.02E-03
Terrestrial eutrophication (mol N_{eq})	4.30E-03	3.75E-03	3.92E-03
Freshwater eutrophication (kg P_{eq})	8.62E-05	7.69E-05	7.98E-05
Marine eutrophication (kg N_{eq})	4.14E-04	3.58E-04	3.76E-04
Freshwater ecotoxicity (CTUe)	1.95E+00	2.31E+00	2.18E+00
Abiotic depletion - resource (kgSb_{eq})	2.78E-07	3.92E-07	3.58E-07

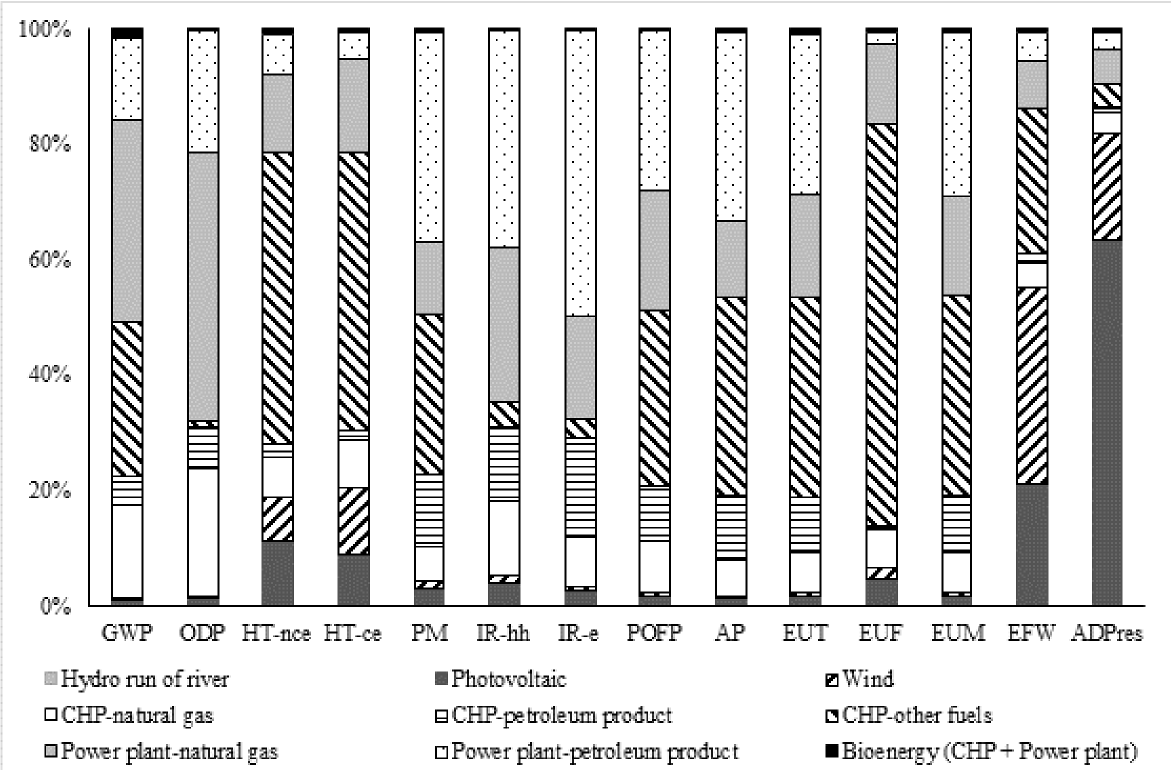

Figure 5. Environmental impact – process contribution in RS.

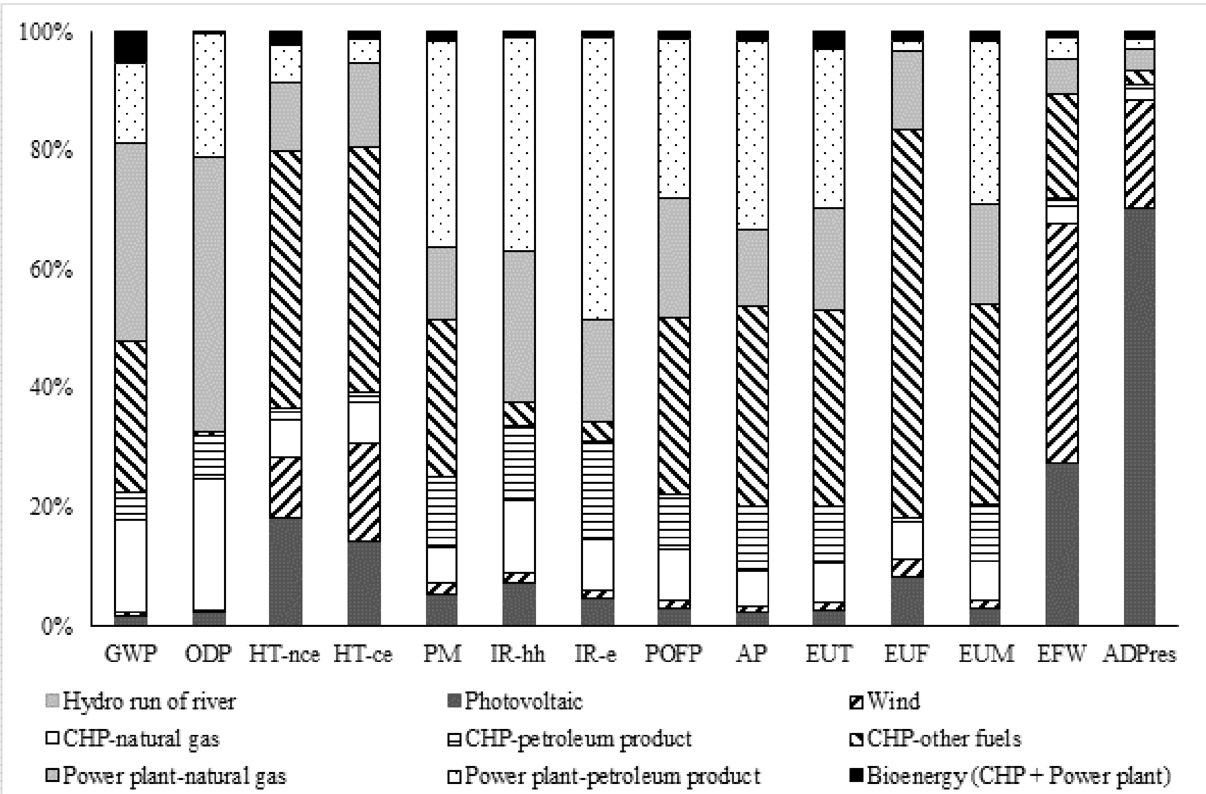

Figure 6. Environmental impact – process contribution in 2030 – BS.

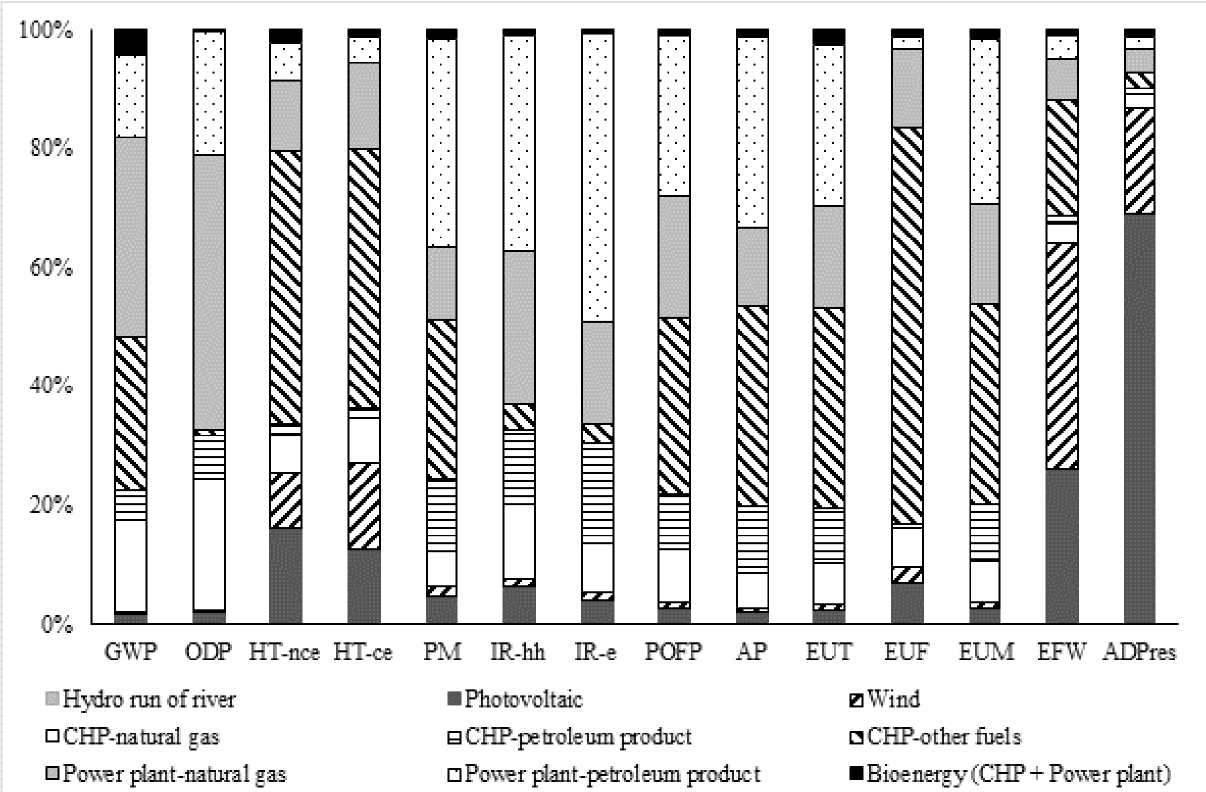

Figure 7. Environmental impact – process contribution in 2030 – DS.

In freshwater ecotoxicity the impact increases of about 19% in the 2030 – BS and 12% in 2030 – DS. The decrease of the impact related to the reduced electricity generation from non – renewable energy technology is totally offset by the increased impact of the electricity generated from photovoltaic and wind power plant.

Wind power plants are the larger contributors to freshwater ecotoxicity accounting for 34% in the RS, 40% in 2030 – BS and 38% in the 2030 – DS.

The increase of the abiotic depletion potential in both scenarios (+41% in 2030 – BS and + 28% in 2030 – DS) 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 (Van Oers et al., 2002).

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

Both the future scenarios are in compliance with the EU energy strategies 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 mix is equal to 24% in RS, and increase up to 36% in 2030 – BS and to 32% in 2030 – DS.

The assessment of the potential contribution of the Sicilian electricity sector to the European energy and climate policy for 2030 was based on the forecasted electricity demand and the global warming potential per kWh of electricity generated in both the forecasted scenarios. The results are recapped in Table 6.

Data analysis highlights that only the 2030 – BS, defined considering a decrease in the future electricity demand and a high penetration of renewables, involves a potential reduction of the GHG emissions and then a positive contribute to the EU climate policy. In the 2030 – DS, although the electricity eco-profile improves in terms of global warming potential, an increase of the GHG emissions occurs compared to the RS due to the electricity demand increase.

Table 6. 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	6.23E-01	22,211	1.38E+07	
2030 - BS	5.48E-01	21,857	1.20E+07	-13.4%
2030 - DS	5.74E-01	24,441	1.40E+07	+1.4%

6 Conclusions

The implementation of low carbon strategies in energy generation 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 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 global energy requirement of 9.6% in 2030 – BS and 7% in 2030 – DS, per kWh of electricity generated. In detail, the non-renewable primary energy demand would decrease by 15% in 2030 – BS and 10.4% in 2030 – DS, compared with the RS. In the same period, renewable primary energy demand would increase by about 42% in 2030 – BS and 28% in 2030- DS as a consequence of high penetration of renewable energy sources.

The significant penetration rate of renewable energy sources would enhance the energy supply security, involving the reduction of imported fossil fuels, compared to the RS.

Both the forecasted scenarios propose a reduction in the primary energy requirements and correspondent GHG emissions per kWh of electricity generated. However, the analysis of a wide range of environmental aspects of sustainability through the multi – indicator approach of the LCA highlights that with the current state of development of electricity technologies generation is not possible to achieve improvements in a whole set of environmental impacts categories declined in potentially conflating domains.

The assessed scenarios would involve an overall reduction in almost all other environmental impact categories, with the exception of freshwater ecotoxicity and abiotic depletion in which electricity from renewable technologies is highly impacting. In detail, the percentage reductions range from 15% for ozone depletion potential in 2030 BS – scenario to 1.5% for human toxicity – non cancer effect in 2030 – DS scenario. The impact on freshwater ecotoxicity increases by 18.7% in 2030 – BS and 12.3% in 2030 – DS, while in abiotic depletion by 41% in 2030 – BS and 28.4% in 2030 – DS.

Then, the definition of energy policies, aimed at minimizing energy and environmental impacts, have to take into account and to identify different and significant environmental aspects. In particular, the results highlight a significant increase of abiotic deletion potential and freshwater ecotoxicity, then a deeper analysis need to be carried out on resource sustainability of a high exploitation of renewable energy sources in the electricity generation and the potential toxicity for human health and ecosystem mainly related to the material employed in the renewable technologies manufacturing and their end-of-life treatment.

With reference to climate change, he study shows that the Sicilian electricity sector can contribute to the European climate policy for 2030. Although the estimated amounts 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.

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