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Life Cycle Assessment of Italian Electricity Scenarios to 2030

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Abstract: The study presents a Life Cycle Assessment (LCA) of Italian electricity scenarios, devised in the Integrated National Energy and Climate Plan (INECP). A fully representative LCA of the national electricity system was carried out, taking into consideration a great number of different power plant typologies for current (2016 and 2017) and future (2030) electricity mixes. The study confirms that LCA can be a powerful tool for supporting energy planning and strategies assessment. Indeed the results put in evidence not only the improvement of the environmental profile from the current to the future mix (the impacts decrease from 2016 to 2030 due to the transition towards renewables, mainly wind and photovoltaic), but also underline the difference between two scenarios at 2030 (being the scenario that includes the strategic objectives of the INECP to 2030 the one showing best environmental profile), providing an evaluation of the effect of different energy policies. For example, in the INECP scenario CO_2 eq/kWh is 46% lower than current scenario and 37% lower than business as usual scenario for 2030. Moreover, considering different impact categories allowed to identify potential environmental trade-offs. The results suggest also the need of future insight on data related to photovoltaic technologies and materials and their future development.

Keywords: electricity scenarios; life cycle assessment; Italian electricity; environmental impacts

1. Introduction

European Commission energy policy at the 2030 horizon aims to strengthen the 20-20-20 objectives and, at the same time, is a precondition for 2050 goals of the long-term strategy to reduce greenhouse gas emissions [1]. In this framework, the Italian Integrated National Energy and Climate Plan (INECP) [2], intends to accelerate the transition from traditional fuels to renewable sources.

Due care must be paid to ensure that the energy and climate objectives are compatible with the objectives relating to the landscape protection, the quality of air and water bodies, the safeguarding of biodiversity and soil protection. As a matter of fact, the necessary measures to increase decarbonisation of the system, involve power plants and infrastructure deployment that have environmental impacts [2].

The present study is aimed at evaluating, from an environmental point of view, the Italian electricity generation scenarios at 2030 (devised in the INECP) and at comparing them with the current electricity generation mix.

At this purpose, Life Cycle Assessment (LCA) methodology according to ISO 14040 [3] has been adopted. According to ISO 14040 [3] LCA is a methodology that "*addresses the environmental aspects and potential environmental impacts throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e., cradle-to-grave)*". LCA can be a powerful tool for supporting energy planning for several reasons:

- For an effective energy transition towards a low carbon system, the reduction of greenhouse gas emissions shall occur over the entire chain of energy production and consumption. LCA allows to evaluate the potential impacts of a system/product taking into account all the processes along the entire life cycle.

- LCA provides an impact assessment of the electricity scenarios not only on climate change, but taking into account a more complex environmental profile, including several environmental impact categories, in order to verify the effects of a policy on the different environmental aspects and to point out potential environmental trade-offs [4].
- An in-depth LCA analysis of the current and future electricity mix is definitely relevant since energy policies promote the electrification of final energy consumptions. The detailed and updated analysis of the current and future mix can be used as a reference in other LCA studies, since the electricity production pervades the life cycle of numerous products and often represents one of the most relevant processes.
- LCA results (detailed for phase and geographic location) represent the basis for monetary valuation of environmental externalities [5].

For these reasons, LCA have been widely used in literature to assess present and future national electricity mix scenarios sustainability [6–9]. Some works put also in evidence issues and explore new methodological solutions. For example, the study [10] on the life-cycle assessment of the large-scale implementation of climate-mitigation technologies, addresses the impacts on the electricity and uses assumptions of technical improvements also in material production technologies. Reference [11] combines different approaches in a "technology hybridized environmental-economic model with integrated scenarios", to predict the environmental impacts of energy policy scenarios. Recent studies evaluate, with a life cycle approach, energy scenarios at a national (Spain [6] and Germany [7]) or regional (Sicilia region in Italy [9]) scale. According to [6], that provides an investigation into the sustainability of the electrical system in Spain, for future scenarios (2030 and 2050), the most ambitious projections in terms of renewable penetration perform best in terms of environmental performance and the scenario considering higher fossil fuel contributions performs worst in all sustainability indicators. As demonstrated in [12] the 2030 New York scenario, based on 70% of renewable energies, dramatically reduces both carbon dioxide emissions and cumulative energy demand. Finally, the life cycle assessment of UK electricity scenarios to 2070 was studied by [8]. According to the LCA results, the decarbonisation of the UK electricity mix introduces many questions regarding sustainability and shows that the level of decarbonisation achieved and the method taken can lead to significantly diverging outcomes, each involving trade-offs and compromises.

In this framework, the present study evaluates the Italian energy strategy, starting from a detailed and fully representative LCA of the Italian electricity system. In order to represent the variability of energy sources, fuels and transformation technologies, the study takes into consideration a great number of different electricity power plant types for current and future electricity mixes. For operation phase of fossil thermoelectric sector, updated primary data for the main air emissions have been used. In fact, also considering the increasing role of electricity as an energy carrier, data quality and representativeness, is a crucial issue in life cycle inventory of electricity supply [13].

Two scenarios at 2030 have been used in this work, in order to evaluate the effect of the electricity system evolution on the environmental indicators. These scenarios are described and utilized as the basis of the Italian Integrated National Energy and Climate Plan [2]. For Italian current electricity system, two years are taken into consideration: 2016 and 2017. Year 2016 is the base year used for INECP scenarios elaboration, while year 2017 is the most recent year for which statistical data were available (when performing the study) and it is considered in order to present an updated LCA of present Italian electricity system.

Goal and scope of the LCA, inventory and impact assessment results are described in the following paragraphs.

2. Materials and Methods

The goal of the present study is the Life Cycle Assessment (ISO 14040 [3]) of electricity generation scenarios in Italy at 2030. In particular, two scenarios developed for the INECP are taken into consideration: the Baseline scenario (2030 BASE) that describes an evolution of the Italian energy system with current policies and measures and the INECP scenario (2030 INECP) that quantifies the strategic objectives of the plan [2].

In this study each scenario is defined by:

- A mix of electricity production technologies and energy sources;
- The efficiency and load factor related to the specific technology.

For future mixes, the technological progress in the electricity conversion technologies was taken into account through enhanced conversion efficiencies and load factors.

Background system evolution in time (as for example global production market of main materials for power plant construction) has not been considered in this study. This can be a critical issue especially for studies on long term scenarios [14]. Nevertheless the results of the present study could help to identify the most relevant background processes and materials production markets, with a role in environmental potential trade-offs which can be investigated in future studies, with a much longer perspective (2050, 2070).

In order to evaluate the evolution of the electricity mix, and consequently the evolution of the environmental profile associated with it, the LCA of the current electricity mix is first presented, taking into consideration years 2016 and 2017.

The functional unit is 1 kWh of electricity Gross National Consumption (GNC) which includes the total gross national electricity generation from all sources (excepted pumped hydro generation), plus electricity imports, minus exports. As regards system boundaries, all phases of the life cycle, from cradle to grave, are included in the analysis: fuel supply, power plant construction, power plant operation and power plant end-of-life.

Since the functional unit refers to GNC and not to the final consumption, transmission and distribution network, as well as the losses associated with it, are excluded from the boundaries of the analyzed system. The impact categories and assessment methods are selected on the basis of Impact Assessment guidelines [15] drawn up by Joint Research Center—European Commission—JRC. Only impact categories reported in the guideline with the level of recommendations I (recommended and satisfactory) and II (recommended but in need of some improvements) are utilized (see Table 1). For assessment methods description and reference, refer to [15].

Table 1. Impact categories taken into consideration in the LCA of the Italian electricity scenarios.

Impact Category	u.m.	Assessment Method	Recommendation Level
Climate Change	(kg CO_2 eq)	Baseline model of 100 years of the IPCC	I
Ozone depletion	(kg CFC^{-11} eq)	Steady-state ODPs	I
Particulate matter	(kg $PM_{2.5}$ eq)	RiskPoll model	I
Ionizing radiation HH	(kBq U235 eq)	Human health effect model	II
Photochemical ozone formation	(kg NMVOC eq)	LOTOS-EUROS as applied in ReCiPe	II
Acidification	(molc H^+ eq)	Accumulated Exceedance	II
Terrestrial eutrophication	(molc N eq)	Accumulated Exceedance	II
Freshwater eutrophication	kg P eq	EUTREND model as implemented in ReCiPe	II
Marine eutrophication	kg N eq	EUTREND model as implemented in ReCiPe	II
Mineral, fossil & ren resource depletion	kg Sb eq	CML 2002	II

Regarding data quality, primary data (statistical data and environmental declarations from Italian power plants) and secondary data (Ecoinvent LCI database [16]) were used, as better specified below. For elaborations the LCA software SimaPro (v8, PRè Consultant, Amersfoort, The Netherlands) was used.

As regards the allocation of impacts between the main product and by-products, the "cut-off" [16] approach was adopted. To the secondary (recycled) materials, only the impacts of the recycling process are assigned (no impact from the primary production of the material). In the case of electricity from wastes, all the impacts of incineration are allocated to the waste treated in the plant (electricity production is burden free). For allocation between heat and electricity in the cogeneration power plants, allocation proportional to the output was used. The fuel is attributed proportionally to the amount of the output product (electricity and heat). This approach was chosen since it is coherent to the method used in Eurostat energy balance.

Statistical data have been elaborated in order to obtain electricity mix detailed by power plant typology. A power plant typology is defined by a combination of fuel in input and transformation technology (e.g., natural gas combined cycle power plant). Since available official data and life cycle inventories present aggregated data for Italian electricity mix, a combination of different official energy statistics has been analyzed and elaborated, in order to consider a complete set of fuels and technologies. As regards thermal power plants, technologies taken into consideration are those reported in the statistical reports published annually by TERNA (the Italian system transmission operator) [17]:

- electricity production only (Only EL): internal combustion (CI), gas turbine (TG), condensing steam (C), combined cycle (CC), repowered (RP);
- combined heat and power production (CHP): internal combustion (CIC), gas turbine (TGC), combined cycle (CCC), counter pressure steam (CPC), condensing steam with bleed (CSC).

Fuels taken into consideration are all those reported in the energy balance published by Eurostat [18]. In addition to thermoelectric (fossil and renewable), the mix includes hydroelectric (reservoir and runoff), wind and photovoltaic plants.

Tables A1–A4, in Appendix A, show Italian current and future electricity mixes, with the details of the power plant typology. The 2016 and 2017 mixes are very similar: natural gas accounted for 39–42% of the total electricity production in Italy. Among renewable sources, hydropower ranks first, covering 11–13% of the total production, followed by solar and wind energy. A share of about 11% of the electricity is imported. For scenario BASE at 2030 a greater penetration of renewable is foreseen especially for hydropower (from 10% to more than 15%), wind power (from 5% to 7.5%) and solar power (from 7% to almost 10%). In the INECP Scenario a phase out of coal is included, with zero contribution at 2030, while the penetration of solar power rises up to more than 20%.

To build the life cycle inventory, both primary and secondary data have been taken into account. For future mixes, the technological progress in the electricity conversion technologies was taken into account through conversion efficiencies and load factors, resulting from the scenarios described in the INECP [2]. Table 2 contains power plant efficiencies taken into consideration for current and future mixes.

Primary data include:

- electricity production and efficiency for each type of power plant (Table 2): Eurostat [18] and TERNA [17] statistical data were used for current mix; scenarios data from the INECP [2] were used for 2030 mixes;
- wind farm load factor: Eurostat data [18] were used for current mix; scenario data from the INECP [2] were used for 2030 mixes (Table 3);
- photovoltaic load factor: Eurostat data [18] were used for current mix; scenario data from the INECP were used for 2030 mixes (Table 3);
- natural gas import market: SNAM data (Sustainability Report and Ten-Year Development Plan) [19] were used;
- oil products input market: data from the Italian Oil Association [20] were used;
- CO_2 emissions during operation of the thermoelectric plants: ISPRA [21] values based on IPCC [22] were used with the exception of "Other Petroleum power plants", for which we used

the values based on environmental declarations of the Italian thermoelectric plants registered to the Community eco-management and audit system—EMAS (Regulation 1221/2009) [23]. Average emission factors per unit of fuel in input (used in this study for current and future scenarios) are reported in Table 4.

Table 2. Power plant electrical efficiencies taken into consideration for current and future mixes.

Fuel	Scenario	CI	TG	C	CC	CIC	TGC	CCC	CPC	CSC
Other bituminous coal	2016			0.39				0.25		
	2017			0.39				0.25	0.11	
	2030 BASE			0.47						
Sub bituminous coal	2016			0.39						
	2017			0.38						
Coke oven gas	2016					0.35		0.32		0.34
	2017					0.38		0.33		0.36
Blast furnace gas	2016					0.32		0.29		0.32
	2017					0.34		0.30		0.32
	2030 BASE							0.30		
	2030 INECP							0.30		
Other recovered gas	2016					0.33		0.30		0.33
	2017					0.36		0.31		0.33
Refinery gas	2016					0.39	0.30	0.26	0.12	0.12
	2017					0.35	0.28	0.26	0.10	0.14
Liquefied petroleum gases	2016							0.31		
	2017						0.35	0.32		
Gas oil and diesel oil (without biofuels)	2016	0.39		0.36				0.47		
	2017	0.39		0.36	0.42			0.47		
Fuel oil	2016	0.38		0.35			0.18	0.16		
	2017	0.38		0.35			0.18	0.16		0.10
Other oil products	2016			0.24				0.23		
	2017			0.23				0.23		
	2030 BASE							0.48		
	2030 INECP							0.49		
Natural gas	2016	0.37	0.32	0.38	0.54	0.41	0.32	0.48	0.20	0.27
	2017	0.37	0.31	0.39	0.54	0.41	0.32	0.49	0.20	0.28
	2030 BASE				0.58	0.45	0.36	0.50		
	2030 INECP				0.54	0.45	0.36	0.50		
Primary solid biofuels	2016	0.41		0.26		0.21			0.20	0.13
	2017	0.42		0.28		0.21			0.20	0.14
	2030 BASE			0.33		0.39				
	2030 INECP			0.33		0.39				
Biogas	2016	0.37	0.32			0.40		0.36		
	2017	0.37	0.32			0.40		0.36		0.16
	2030 BASE	0.40	0.40			0.40				
	2034 INECP	0.40	0.40			0.40				
Renewable municipal waste	2016			0.25		0.31			0.30	0.20
	2017			0.25		0.30			0.29	0.20
	2030 BASE					0.23			0.23	0.23
	2030 INECP					0.23			0.23	0.23
Other liquid biofuels	2016	0.41			0.49	0.40			0.40	0.36
	2017	0.42			0.48	0.40			0.40	0.37
Industrial wastes	2016			0.26						0.14
	2017			0.26		0.22	0.10			0.14
Non-renewable municipal waste	2016			0.25		0.31			0.30	0.20
	2017			0.25		0.30			0.29	0.20
	2030 BASE					0.23			0.23	0.23
	2030 INECP					0.23			0.23	0.23

Table 3. Wind and Photovoltaic load factors for current and future mixes.

Energy Source	2016	2017	2030 Base	2030 INECP
Wind	1885	1822	2029	2029
Photovoltaic	1146	1239	1329	1329

Table 4. CO_2 average emission factors per unit of fuel in input, in operation phase of power plants.

Power Plant Type	**CO_2 (kg/MJ_{in})**
Natural Gas	0.0564
Coal	0.0939
Fuel Oil	0.0767
Gas Diesel Oil	0.0741
LPG	0.0642
Pet. TAR	0.1211

- NOx, SOx and PM10 emissions during operation of thermoelectric fossil power plants: a selection of data extracted from the Environmental Declaration (requested by EMAS Regulation) of Italian Thermoelectric plants were elaborated. The elaboration included 102 plants, which constitutes a sample of the Italian thermoelectric power plants. About half of the power plants were excluded from the calculation of the average emissions due to incompleteness or because they are multi-fuel plants. The sample of power plants used for the calculation of the average emissions covers from 30% (oil power plants) to about 90% (coal power plants) of the total electricity production in Italy (year 2017), depending on the type of power plants, as reported in Table 5. Average emission values are reported in Table 6.

Table 5. Description of the sample of power plants used for the calculation of the average emissions.

Power Plant Type	**N° Power Plants in the Sample**	**Electricity Production (% on Total)** [1]
Natural Gas	35	53%
Coal	8	93%
Fuel Oil	1	30%
Other Oil products	1	56%
Total (fossil thermoelectric)	**45**	**56%**

[1] Sum electricity production of the sample/total electricity production.

Table 6. Calculated average emissions per unit of fuel in input, in operation phase of power plants.

Power Plant Type	**SOx (g/MJ_{in})**	**NOx (g/MJ_{in})**	**PM 10 (g/MJ_{in})**
Natural Gas	0.00	1.73×10^{-2}	1.88×10^{-5}
Coal	2.99×10^{-2}	3.99×10^{-2}	1.25×10^{-3}
Fuel Oil	3.22×10^{-2}	2.47×10^{-2}	3.33×10^{-3}
Pet TAR	1.51×10^{-2}	2.06×10^{-2}	2.03×10^{-4}

Exceptions are coke oven gas and blast furnaces gas for which secondary (Ecoinvent 3.3 [16]) data have been used.

Secondary data from database Ecoinvent [16] have been used for power plants construction and dismantling, as well as for all background systems.

3. Results

The effects of policies in the INECP scenario are very evident compared to the baseline scenario. Both 2030 scenarios lead to an increase in renewables, but the strategic objectives of the plan in INECP scenario make the transition to renewables decidedly evident, bringing to zero the electricity production from coal and driving wind plus photovoltaic share in the mix to more than 30%.

In the following graph (Figure 1) the percentage contributions of the different power plants to the mix are highlighted and the electricity mix by the European Commission scenario PRIMES 2016 (2030 EU-REF IT) [24] is also added for comparison. The EU Reference Scenario is one of the European

Commission's key analysis tools in the areas of energy, transport and climate action. It uses the PRIMES model for energy and CO_2 projections [24].

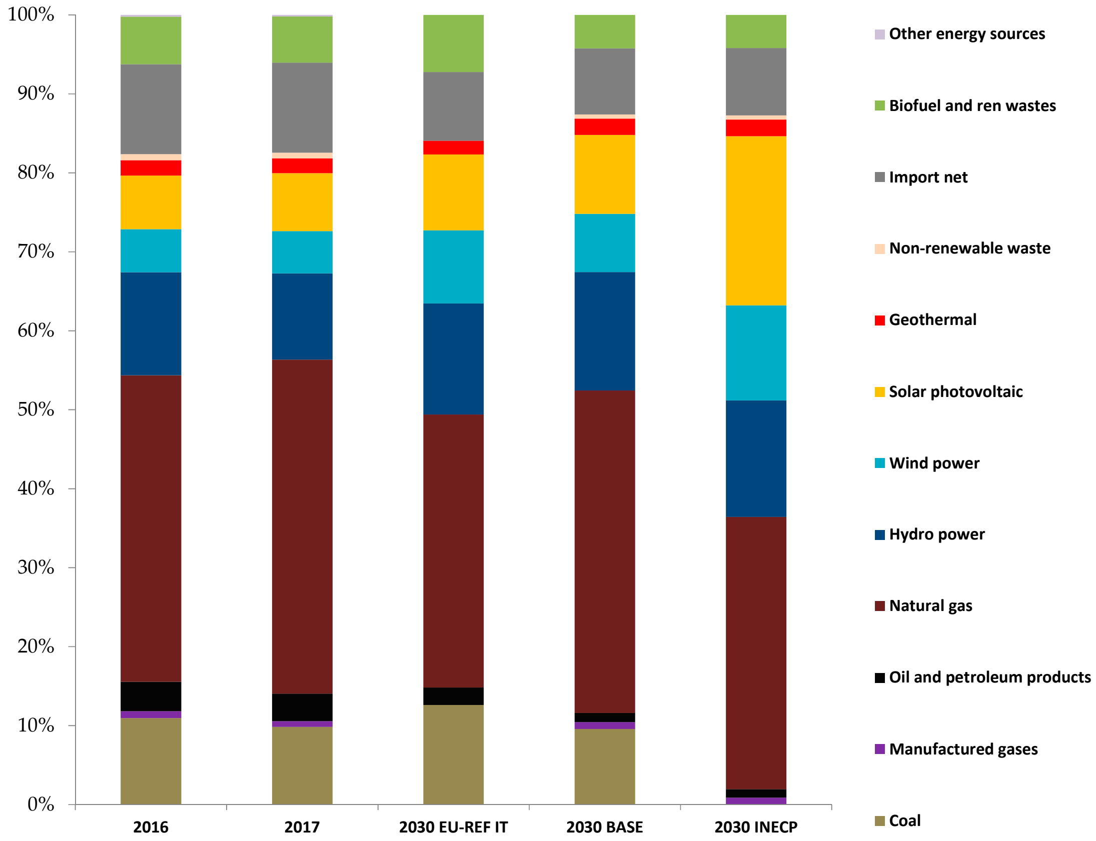

Figure 1. Contribution of different power plants to current and future electricity mixes.

Table 7 shows the results of the impact assessment. For each category, the impact along the entire life cycle of the electricity mix is reported, referred to the functional unit, 1 kWh of GNC.

Table 7. Life Cycle Impact Assessment results per 1 kWh of electricity GNC.

Impact Category	u.m.	2016	2017	2030 BASE	2030 INECP	2030 EU-REF IT
Climate Change	kg CO_2 eq	4.18×10^{-1}	4.17×10^{-1}	3.57×10^{-1}	2.26×10^{-1}	3.14×10^{-1}
Ozone depletion	kg CFC-11 eq	3.79×10^{-8}	4.05×10^{-8}	3.72×10^{-8}	3.16×10^{-8}	3.17×10^{-8}
Particulate matter	kg PM2.5 eq	7.47×10^{-5}	7.48×10^{-5}	6.30×10^{-5}	5.73×10^{-5}	6.10×10^{-5}
Ionizing radiation HH	kBq U235 eq	2.87×10^{-2}	2.89×10^{-2}	1.98×10^{-2}	1.96×10^{-2}	2.02×10^{-2}
Photochemical ozone formation	kg NMVOC eq	4.67×10^{-4}	4.71×10^{-4}	4.08×10^{-4}	3.14×10^{-4}	3.80×10^{-4}
Acidification	molc H^+ eq	8.97×10^{-4}	8.93×10^{-4}	7.48×10^{-4}	5.69×10^{-4}	7.23×10^{-4}
Terrestrial eutrophication	molc N eq	1.63×10^{-3}	1.61×10^{-3}	1.41×10^{-3}	1.06×10^{-3}	1.39×10^{-3}
Freshwater eutrophication	kg P eq	9.41×10^{-5}	9.07×10^{-5}	7.43×10^{-5}	4.55×10^{-5}	7.80×10^{-5}
Marine eutrophication	kg N eq	1.88×10^{-4}	1.84×10^{-4}	1.29×10^{-4}	9.51×10^{-5}	1.25×10^{-4}
Mineral, fossil & ren resource depletion	kg Sb eq	3.22×10^{-6}	3.18×10^{-6}	3.33×10^{-6}	6.05×10^{-6}	3.05×10^{-6}

For the sake of completeness, a comparison is also provided with the 2030 scenario developed by the European Commission for Italy (2030 EU-REF IT).

The INECP scenario is the one with the best environmental performance, resulting in the least impact for almost all categories. The only notable exception is the impact category "Mineral, fossil & ren resource depletion": the strong increase in photovoltaic (more than double in percentage compared to the baseline scenario) is the main reason for the greater impact and is essentially due to the metals present in the inverter and to the aluminium frame and the support structures of the modules. This impact could be significantly reduced in the future thanks to the diffusion of innovative photovoltaic solutions, as for example double-sided glass-glass modules. It should be reminded that in the present study only the evolution of power plant efficiencies and load factors is taken into consideration in the scenarios, and no hypothesis is formulated about changes in the background system, as for example global production market of main materials such as aluminium. This could be an interesting task for future insights, above all on wind and photovoltaic technologies, for which background processes have a higher impact than operation and maintenance phase.

Results (Figure 2) show a general decrease from 2016 to 2030 of the impacts of the Italian electricity mix. The most marked decrease is observed for Climate Change (−46% compared to 2016 in the INECP case) and Water Eutrophication (−51% compared to 2016 in the PNIEC case) impact categories. The decrease is driven by the transition to renewables (mainly wind and photovoltaic).

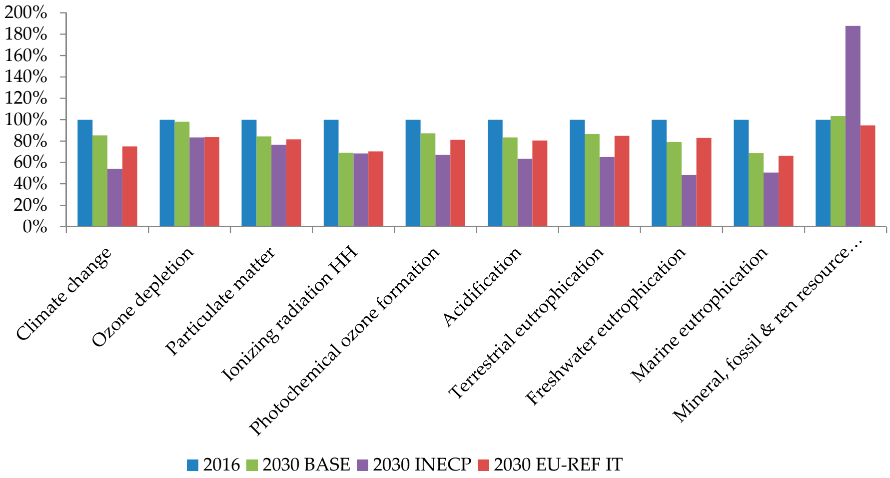

Figure 2. Comparison between Life cycle impact assessment of current and future mixes. Results in percentage respect to 2016.

The decrease of Ionizing Radiation impact is due to the lowest share of imported electricity, since for this impact category, nuclear energy (absent in the Italian mix but present in the European import mix) has the greatest effect.

For all the impact categories, BASE scenario results are similar to the results coming from EU-REF IT scenario.

Table 8 highlights the category of power plants that most contributes to the impact, for both scenarios at 2030.

Table 8. Main contributor to the impact for Base and INECP scenarios.

Impact Category	Main Contributor to the Impact
Climate Change	Natural gas power plants
Ozone Depletion	Natural gas power plants
Particulate Matter	Natural gas power plants and Photovoltaic (INECP)
Ionizing radiation	Imported electricity
Photochemical Ozone Formation	Natural gas power plants
Acidification	Natural gas power plants
Terrestrial eutrophication	Natural gas power plants
Marine eutrophication	Natural gas power plants
Freshwater eutrophication	Coal power plants(2030 BASE) Net Import (INECP)
Mineral fossil and renewable resource depletion	Photovoltaic system

Each technology contribution is determined by two factors: the specific impact of the single source/production technology and the share of the single source/production technology in the electricity mix. Natural gas power plants contribution is in general due to the high share in the mixes.

More in detail, for both scenarios at 2030, BASE and INECP:

- Climate change: main contribution comes from electricity produced by natural gas power plants.
- Ozone depletion: main contribution comes from electricity produced by natural gas power plants (it is mainly related to fuel upstream phase, and in particular to the transport of gas through pipeline and to the refrigerants used in the compression stations).
- Particulate matter: main contribution comes from electricity produced by natural gas power plants; in the INECP scenario it comes also from photovoltaic, due to the market for silicon wafer production. Emissions are linked to China energy mix, used for photovoltaic silicon wafer production.
- Ionizing radiation: as above mentioned, main contribution comes from imported electricity.
- Photochemical ozone formation: main contribution comes from electricity produced by natural gas power plants.
- Acidification: in addition to natural gas power plants also the impacts relating to imported electricity and coal plants (for 2030 BASE only) should be highlighted. The impacts are substantially associated with the coal upstream (also in the case of imported electricity).
- Terrestrial eutrophication and marine eutrophication: main contribution is associated to natural gas, coal power plants and import. It must be underlined also the contribution deriving from biomass power plants (this is due in part to the cultivation phase of vegetables dedicated to bioliquid production).
- Freshwater eutrophication: main contribution comes from coal upstream. According to background life cycle inventory data, the impact is mainly due to coal mining operations. As concerns INECP main contribution comes from Net Import.
- Mineral fossil and renewable resource depletion: main contribution comes from photovoltaic systems, due to the aluminium used for the frame and for the support structure of the modules, as well as to the metals present in the inverter.

Figures 3 and 4 put in evidence, for each impact category, the relative contribution of each energy source.

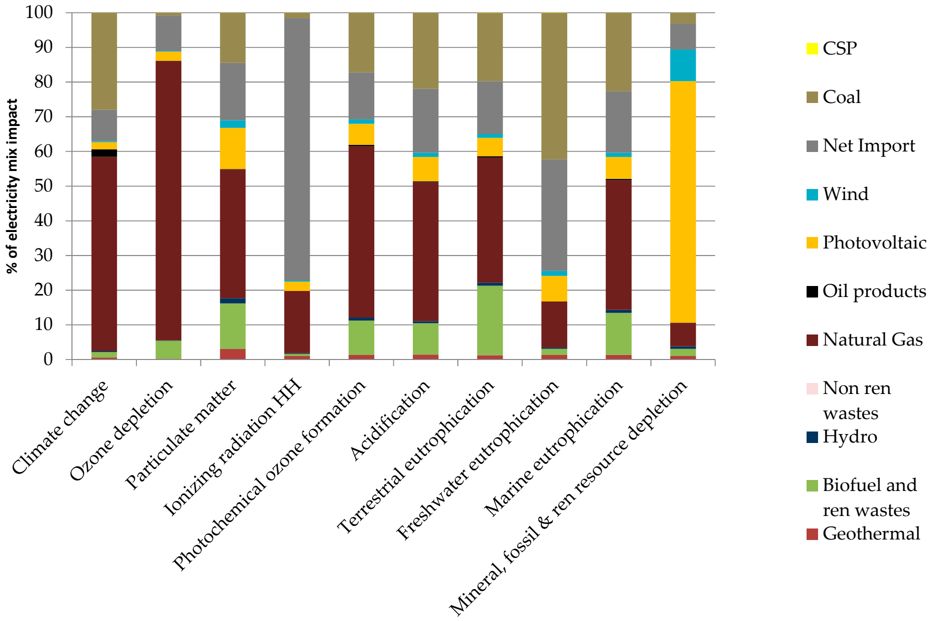

Figure 3. Contribution of different typologies of power plant to the overall impact of the 2030 BASE scenario electricity mix for Italy.

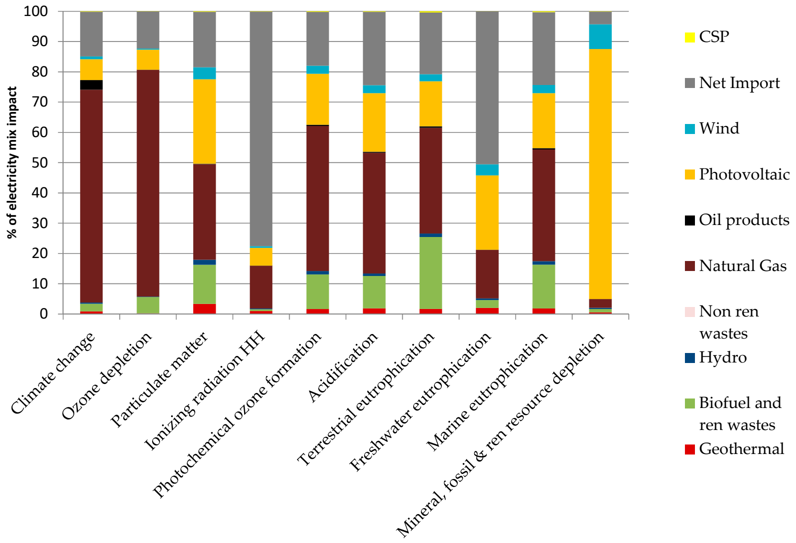

Figure 4. Contribution of different typologies of power plant to the overall impact of the 2030 INECP scenario electricity mix for Italy.

More in detail, regarding climate change, annual CO_2 eq emissions due to Italian electricity mix amount to 136–138 Mt/year in 2016–2017, 122 Mt/year in 2030 for the BASE scenario, and 76 Mt/year in 2030 for the INECP scenario.

The main driver of this trend is the decrease in the share of electricity produced from coal and, to a lesser extent, from oil and imported electricity. Finally the increase in the average efficiency of the generation mix also plays a role in reducing CO_2 eq emissions.

The contribution of natural gas power plants to the CO_2 eq emissions is strongly influenced by the fact that the share in the mix of electricity produced by natural gas power plant stands at high values (from 34% to 42%). On the other hand, coal plants with a much lower share in the mix, 9–12% (in the case of the INECP scenario it is equal to 0%), cover from 25% to 35% of the impact. In no case do wind, photovoltaic and hydropower contribute significantly to the CO_2 eq emissions of the mix, despite of shares in the mix far from negligible (10–15% for hydroelectric, 5–11% for wind, 7–21% for photovoltaic) (Figure 5).

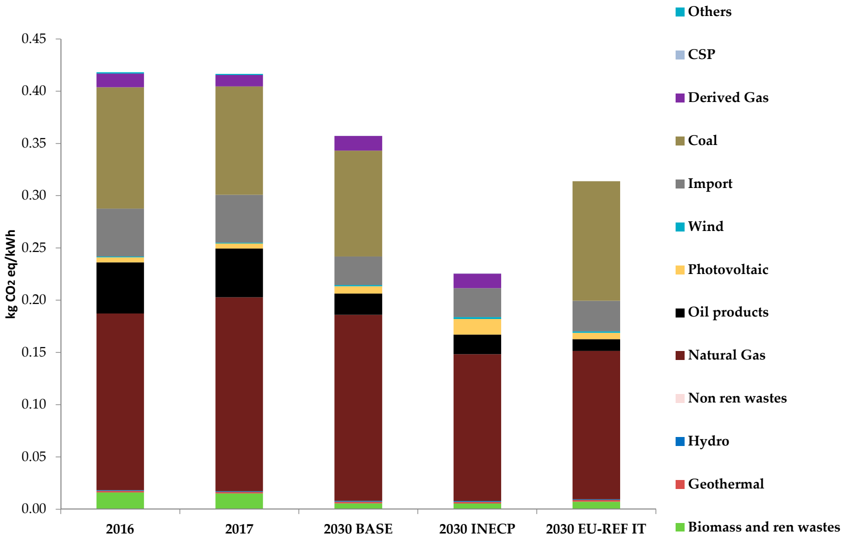

Figure 5. CO_2 eq/kWh for current and future electricity mixes. The contribution of different typologies of power plant is highlighted.

4. Discussion and Conclusions

According to ISO 14040, LCA results can be elaborated trough two optional steps: normalization and weighing. Both can help in interpretation of the results, but can add elements of subjectivity to the evaluation.

In this study, it was decided to leave out weighting, which should involve decision-makers in the process. Conversely, normalization was carried out, which allows to rank and compare the different impacts of a system and, although not devoid of limitation, is a great aid in looking at scenarios environmental profile as a whole.

Even though the limitations reported in [25] have to be considered, normalisation has a relevant role when LCA is aimed at supporting policy makers to ensure that the focus is put on most relevant aspects and for communication purposes.

In normalization JRC's recommendations [25] have been taken into consideration. In view of the international nature of energy supply chains, it was decided to use normalization factors on a global scale. The normalisation factors represent the total impact of a reference region for a certain impact category (e.g., Climate Change, Eutrophication, etc.) in a reference year.

The standardization factors used are those implemented in the Simapro v.8 software and referring to the JRC table version 0.1.1-15/12/2015 (available from: https://eplca.jrc.ec.europa.eu/LCDN/developerILCD.xhtml), developed as the first version in the context of the work described in [25].

For each impact indicator, the impact assessment result is divided by the global value (i.e., deriving from all human activities) of the same indicator, on a per capita basis. In order to apply the normalization, the Italian gross national electricity consumption per capita per year (electricity yearly GNC divided by the Italian population) was calculated for current and future scenarios. The following graphs show normalized LCA results (dimensionless).

In all scenarios (current, i.e., 2016 and 2017 results are very similar. In the graph only 2016 results are shown, 2030 BASE and 2030 INECP), most of the impact categories present similar values (lower than 0.10). It is notable that, also in the case of water eutrophication impact categories for which life cycle impact assessment showed the higher reduction from current to INECP scenario, the normalized results are lower than 0.10. On the other hand the Climate Change category and the Ionizing Radiation category present definitely higher values (0.18–0.33 and 0.45–0.66 respectively).

The impact on resource depletion, the only category which increase along the time horizon of the assessment, remains, as normalized value, under 0.20, also in the case of INECP scenario (Figures 6–8)

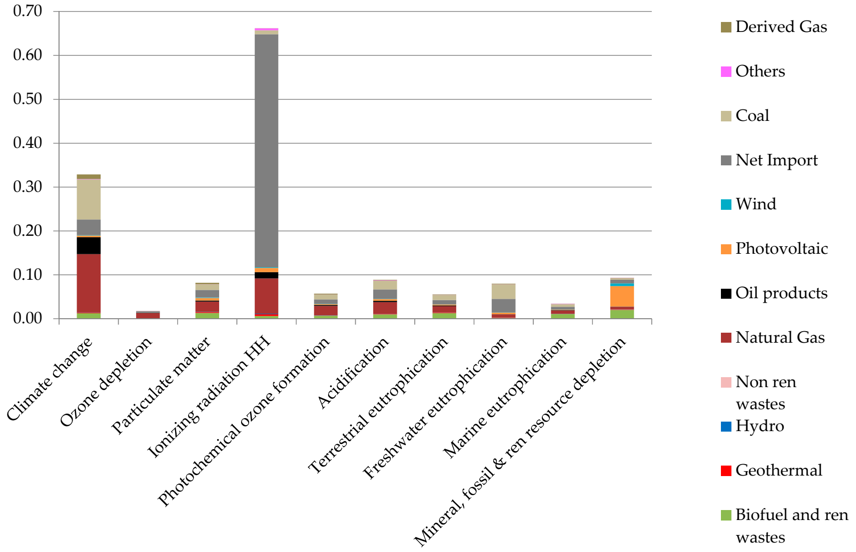

Figure 6. Normalized results for current Italian gross national (2016) electricity consumption per capita per year.

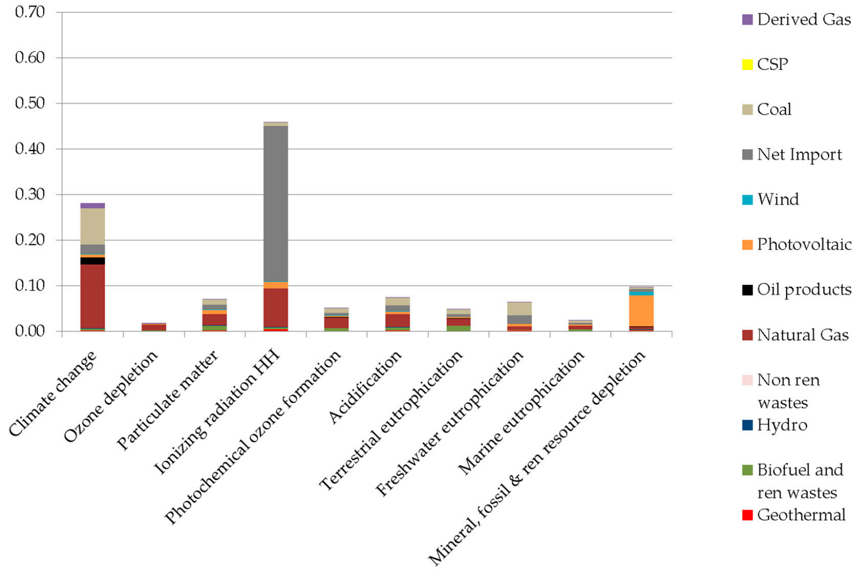

Figure 7. Normalized results for 2030 BASE Italian gross national electricity consumption per capita per year.

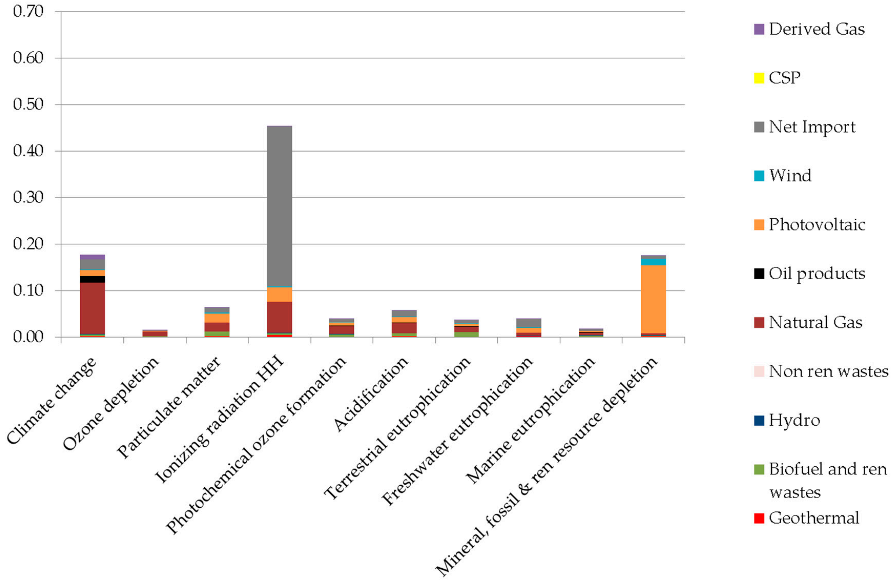

Figure 8. Normalized results for 2030 INECP Italian gross national electricity consumption per capita per year.

In conclusion, the present study confirms that LCA can be a powerful tool for supporting energy planning and strategies assessment. As a matter of fact, results put in evidence not only the improvement of the environmental profile from the current to the future mix, but also underline the difference between the baseline scenario and the INECP one, providing an evaluation of the effect of different energy policies. According to LCA results, the impacts of the Italian electricity mix decrease from 2016 to 2030 due to the transition to renewables, mainly wind and photovoltaic. Climate Change impact decreases by about 46% compared to 2016. Most important for policy implication, the scenario that includes the strategic objectives of the Integrated National Plan for Energy and Climate to 2030 is the one with the best environmental profile (INECP scenario CO_2 eq/kWh are 37% lower than 2030 BASE scenario). Moreover, considering not only climate change but a set of different impact categories, allowed to identify potential environmental trade-off, thus obtaining a more complete environmental assessment of energy policies.

The only potential environmental trade-off (even if slight looking at normalized results), seems to occur between climate change and the impact category related to resources depletion. The impact on resource depletion is mainly associated with the metals present in the inverter and especially with the aluminium frame and structure of the photovoltaic modules. This finding can address subsequent studies and insights. First of all, a big effort is demanded for improving and updating the inventory data relating to the photovoltaic modules (in the present study, only secondary data were used for the construction and end-of-life phase). Particular attention must also be paid to the aspects relating to the recycling processes (especially for aluminum) also from a methodological point of view (allocation of impact on primary or secondary materials), since a significant reduction in resource depletion impact may depend on recycling. Photovoltaic only in relatively recent years deeply penetrates energy mixes and for this reason, data on recycling and on the secondary products market are not widely available. Sensitivity analysis on various recycling hypotheses could be useful [26].

Finally, in the context of improving inventory data, the technological evolution towards new photovoltaic solutions (for example heterojunction modules [27]) should also be taken into consideration especially in the case of longer-term scenarios, like those in 2050, a horizon identified by Italy for a deep decarbonisation of the energy sector. As mentioned, beside assessing the environmental effect of the energy policy, the study demonstrates that LCA is a powerful tool in supporting decision makers especially dealing with future national energy plan. Nevertheless, although well beyond the scope of the present study, it should be underlined that also economic and social impacts must be taken into account in policy and decision making in energy sector [6]. Sustainable development of energy systems, in fact, requires that all three pillars of, environmental, economic and social, are taken into consideration [28].

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Current (2016) Italian electricity mix.

Source	Total %	Only EL %	*CI %*	*TG %*	*C %*	*CC %*	CHP %	*CIC %*	*TGC %*	*CCC %*	*CPC %*	*CSC %*
Coal	10.96	10.91	-	-	10.91	-	0.04	-	-	0.04	0.00	-
Other bituminous coal	10.88	10.84	-	-	10.84	-	0.04	-	-	0.04	0.00	-
Sub-bituminous coal	0.08	0.08	-	-	0.08	-	-	-	-	-	-	-
Manufactured gases	0.86	-	-	-	-	-	0.86	0.04	-	0.43	-	0.39
Coke oven gas	0.23	-	-	-	-	-	0.23	0.01	-	0.12	-	0.11
Blast furnace gas	0.62	-	-	-	-	-	0.62	0.03	-	0.31	-	0.29
Oil and petroleum products	3.73	0.62	0.08	0.00	0.54	0.00	3.11	0.01	0.13	2.89	0.04	0.05
Refinery gas	0.61	-	-	-	-	-	0.61	0.01	0.11	0.41	0.03	0.04
Liquefied petroleum gases	0.01	-	-	-	-	-	0.01	-	0.00	0.01	-	0.00
Gas oil and diesel oil (without biofuels)	0.13	0.12	0.02	-	0.11	-	0.01	-	0.00	0.01	0.00	0.00
Fuel oil	0.52	0.47	0.06	0.00	0.40	0.00	0.06	0.00	0.01	0.04	0.00	0.00
Other oil products	2.46	0.03	-	-	0.03	-	2.43	-	-	2.43	-	-
Natural gas	38.82	13.84	0.08	0.11	0.11	13.55	24.97	2.50	1.37	20.66	0.23	0.21
Renewables and biofuels	33.24											
Hydro power	13.06											
Wind power	5.44											
Solar photovoltaic	6.80											
Geothermal	1.94											
Primary solid biofuels	1.27	0.69	0.09	-	0.60	-	0.58	0.17	0.00	-	0.06	0.35
Biogas	2.54	0.95	0.93	0.01	0.00	0.00	1.60	1.59	0.00	0.01	-	0.00
Renewable municipal waste	0.74	0.38	-	-	0.38	-	0.37	0.11	0.00	-	0.04	0.22

Table A1. *Cont.*

Source	**Total %**	**Only EL %**	*CI %*	*TG %*	*C %*	*CC %*	**CHP %**	*CIC %*	*TGC %*	*CCC %*	*CPC %*	*CSC %*
Other liquid biofuels	1.45	1.01	0.34	0.00	-	0.67	0.43	0.13	0.00	-	0.05	0.26
Non-renewable waste	0.77	0.39	-	-	0.39	-	0.38	0.11	0.00	-	0.04	0.23
Industrial wastes	0.03	0.02	-	-	0.02	-	0.01	0.00	-	-	0.00	0.01
Non-renewable municipal waste	0.74	0.38	-	-	0.38	-	0.37	0.11	0.00	-	0.04	0.22
Import net	11.40											
other energy sources	0.23											
Electricity GNC	100.00											

Table A2. Current (2017) Italian electricity mix.

Source	**Total %**	**Only EL %**	*CI %*	*TG %*	*C %*	*CC %*	**CHP %**	*CIC %*	*TGC %*	*CCC %*	*CPC %*	*CSC %*
Coal	9.84	9.79	-	-	9.79	-	0.04	-	-	0.04	0.00	-
Other bituminous coal	9.83	9.79	-	-	9.79	-	0.04	-	-	0.04	0.00	-
Sub-bituminous coal	0.01	0.01	-	-	0.01	-	-	-	-	-	-	-
Manufactured gases	0.74	-	-	-	-	-	0.74	0.04	-	0.40	-	0.30
Coke oven gas	0.25	-	-	-	-	-	0.25	0.01	-	0.14	-	0.10
Blast furnace gas	0.44	-	-	-	-	-	0.44	0.02	-	0.24	-	0.18
Other recovered gas	0.05	-	-	-	-	-	0.05	0.00	-	0.03	-	0.02
Oil and petroleum products	3.47	0.61	0.07	0.00	0.54	0.00	2.87	0.01	0.13	2.62	0.03	0.07
Refinery gas	0.57	-	-	-	-	-	0.57	0.01	0.11	0.36	0.03	0.06
Gas oil and diesel oil (without biofuels)	0.14	0.12	0.01	-	0.11	-	0.02	-	0.00	0.01	0.00	0.00
Fuel oil	0.51	0.46	0.05	0.00	0.40	0.00	0.06	0.00	0.01	0.03	0.00	0.01
Other oil products	2.24	0.03	-	-	0.03	-	2.21	-	-	2.21	-	-
Natural gas	42.30	16.15	0.08	0.16	0.11	15.79	26.16	2.73	1.37	21.61	0.21	0.25
Renewables and biofuels	31.32											
Hydro power	10.91											
Wind power	5.35											
Solar photovoltaic	7.35											
Geothermal	1.87											
Primary solid biofuels	1.27	0.66	0.09	-	0.58	-	0.61	0.17	0.00	-	0.06	0.37
Biogas	2.50	0.89	0.88	0.01	0.00	0.00	1.61	1.60	0.00	0.01	-	0.00
Renewable municipal waste	0.72	0.35	-	-	0.35	-	0.37	0.11	0.00	-	0.04	0.23
Other liquid biofuels	1.34	0.93	0.31	0.00	-	0.61	0.42	0.12	0.00	-	0.04	0.25
Non-renewable waste	0.75	0.37	-	-	0.37	-	0.38	0.11	0.00	-	0.04	0.23
Industrial wastes	0.03	0.02	-	-	0.02	-	0.01	0.00	-	-	0.00	0.01
Non-renewable municipal waste	0.72	0.35	-	-	0.35	-	0.37	0.11	0.00	-	0.04	0.23
Import net	11.38											
other energy sources	0.20											
Electricity GNC	100.00											

Table A3. Future (2030 BASE) Italian electricity mix.

Source	**Total %**	**Only EL %**	*CI %*	*TG %*	*C %*	*CC %*	**CHP %**	*CIC %*	*TGC %*	*CCC %*	*CPC %*	*CSC %*
Coal	9.56	9.56	-	-	9.56	-	-	-	-	-	-	-
Other bituminous coal	9.56	9.56	-	-	9.56	-	-	-	-	-	-	-
Manufactured gases	0.86	-	-	-	-	-	0.86	-	-	0.86	-	-
Blast furnace gas	0.86	-	-	-	-	-	0.86	-	-	0.86	-	-
Oil and petroleum products	1.20	-	-	-	-	-	1.20	-	0.00	1.20	-	-
Other oil products	1.20	-	-	-	-	-	1.20	-	-	1.20	-	-
Natural gas	40.76	15.67	-	-	-	15.67	25.09	3.91	0.61	20.57	-	-
Renewables and biofuels	38.59											
Hydro power	15.00											
Wind power	7.38											
Solar photovoltaic	9.95											
Geothermal	2.07											
Primary solid biofuels	2.10	1.95	-	-	1.95	-	0.15	0.15	-	-	-	-
Biogas	1.67	0.62	0.61	0.01	0.00	0.00	1.05	1.05	0.00	0.00	-	0.00
Renewable municipal waste	0.43	-	-	-	-	-	0.43	0.15	0.00	-	0.06	0.21
Non-renewable waste	0.43	-	-	-	-	-	0.43	0.15	0.00	-	0.06	0.21
Non-renewable municipal waste	0.43	-	-	-	-	-	0.43	0.15	0.00	-	0.06	0.21
Import net	8.40											
CSP	0.20											
Electricity GNC	100.00											

Table A4. Future (2030 INECP) Italian electricity mix.

Source	Total %	Only EL %	*CI %*	*TG %*	*C %*	*CC %*	CHP %	*CIC %*	*TGC %*	*CCC %*	*CPC %*	*CSC %*
Manufactured gases	0.86	-	-	-	-	-	0.86	-	-	0.86	-	-
Blast furnace gas	0.86	-	-	-	-	-	0.86	-	-	0.86	-	-
Oil and petroleum products	1.20	-	-	-	-	-	1.20	-	0.00	1.20	-	-
Other oil products	1.20	-	-	-	-	-	1.20	-	-	1.20	-	-
Natural gas	34.15	2.31	-	-	-	2.31	31.84	1.71	2.15	27.99	-	-
Renewables and biofuels	53.92											
Hydro power	14.60											
Wind power	11.88											
Solar photovoltaic	21.22											
Geothermal	2.09											
Primary solid biofuels	1.90	1.77	-	-	1.77	-	0.13	0.13	-	-	-	-
Biogas	1.71	0.64	0.62	0.01	0.00	0.00	1.08	1.07	0.00	0.00	-	0.00
Renewable municipal waste	0.51	-	-	-	-	-	0.51	0.15	0.00	-	0.06	0.31
Non-renewable waste	0.51	-	-	-	-	-	0.51	0.15	0.00	-	0.06	0.31
Non-renewable municipal waste	0.51	-	-	-	-	-	0.51	0.15	0.00	-	0.06	0.31
Import net	8.46											
CSP	0.89											
Electricity GNC	100.00											

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