



Environmental assessment of multiple “cleaner electricity mix” scenarios within just energy and circular economy transitions, in Italy and Europe

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ABSTRACT

The current European context, affected by the dramatic conflict between Russia and Ukraine and the related energy and food shortages, is putting a strain on the natural gas availability of the European member states. The latter are forced to new negotiations with other potential energy suppliers, to urgent internal measures to reduce energy demand and, at the same time, to fulfil their commitments to internationally agreed climate targets, where the energy transition is a key strategy. A sustainable energy transition strategy is also essential in circular economy implementation (CE), requiring the replacement of fossil energies with renewable ones. In turn, the energy transition should meet the CE principles to reduce the consumption of natural resources and the contribution to climate change. In this context, this study assesses the environmental impacts of the Italian and EU electricity mixes under different governmental and research scenarios and perspectives, by means of the Life Cycle Assessment approach (Midpoint and Endpoint LCA). Results show that the shift from the BAU electricity mix (year 2021) to the emergency Government plan scenario (2021–2023) replacing 14% of Russian natural gas by means of 42% oil and coal and 58% renewables slightly reduces the contribution to Midpoint LCA impact indicators, including global warming and fossil resource scarcity, while still contributing to particulate matter formation, terrestrial acidification, eco-toxicity and water consumption. The contribution to global warming further decreases in the other modelled scenarios, where natural gas is assumed to decrease from 30% to a high 60% in favour of renewables (Governmental plan 2030 scenario). Other impacts, in particular terrestrial and human toxicity, are instead expected to worsen, calling for much needed improvement of renewable technologies. Further, the Endpoint LCA impact indicators, expressed as DALY (human health damage), lost species potential (biodiversity damage) and increased costs for the extraction of mineral and fossil resources, improve in the Governmental Plan 2030 scenario and other modelled options. LCA shows to be a key method for the energy transition, in order to identify hotspots of modelled electricity scenarios and suggest more environmentally, circular and socially just improvement solutions. The adoption of the concept of CE in energy transition entails the expansion of the boundaries of an LCA to include the end-of-life of renewable technologies (so-called “cradle to cradle” approach) and the assessment of the most successful options to mitigate the environmental and social impacts of energy transition.

1. Introduction

The start of the war between Russia and Ukraine has roiled all the world for its dramatic consequences on population and the environment (Smit et al., 2022). Moreover, the effects on energy markets have been very high as prices of natural gas have recorded higher values than ever in the last decade contributing in turn to record-high wholesale electricity prices (Tollefson, 2022).

The conflict has forced many European Union (EU) countries including Italy to reconsider their suppliers of energy beyond Russia as well as adopting urgent measures in order to meet the domestic demand of natural gas (European Commission, 2022a, b) and energy in general. Overall, the EU imported before the conflict about 40% of natural gas from Russia, but some member States had a even much higher dependence, as they imported their natural gas purchases 100% from Russia (Tollefson, 2022). Furthermore, what is perhaps even more troubling, is

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that ultimately, the conflict is also challenging the efforts of EU member states in their decarbonization path and commitments towards the climate goals (Dennison, 2022; Gatto, 2022; Pastore et al., 2022).

1.1. The EU energy policy context

In order to create a basis for energy policies, the so-called “European Union taxonomy” was proposed by the European Commission, which classifies certain fossil gas and nuclear energy processes as transitional activities useful to contribute to the EU climate goals. This taxonomy will become effective as of 1 January 2023 if both the European Parliament and the Council will finally approve it (European Parliament, 2022a).

If the scope of the energy problem is expanded to the entire European Union, an increasing awareness of the importance of the adoption of energy savings measures appears evident. For example, the French Government evidenced that “*the only way to avoid a crisis is to substantially reduce energy consumption for the next six months. Every business will be required to have an “energy sobriety” plan in place to cut consumption by this fall*”.¹

1.2. The Italian energy situation

In Italy, natural gas has a 38.5% share of gross domestic energy consumption, compared with the 35.5% of oil and 17.3% of renewables (Italian Ministry of Environment and Protection of Territory and Sea et al., 2021). Natural gas is almost entirely imported from abroad, since the domestic production is very low (3.34 billion cubic meters) compared to the demand (76.1 billion cubic meters). In the year 2020, Italian primary energy demand was 166.2 Mtoe (IEA, 2022) compared with about 107.5 Mtoe of final energy uses. Out of these final uses, electricity (from fossil fuels and renewables) was about 24 Mtoe, namely 22.32% of total final uses. Electricity production and consumption will be the main focus of the present study, to gradually replace electricity imports as well as production from fossil powered plants, mainly natural gas (IEA, 2022).

After the start of the conflict between Russia and Ukraine, the Italian Ministry for the Ecological Transition adopted a “National Plan for the containment of natural gas consumption” (Ministry of Ecological Transition, 2022) where the most urgent measures needed to cover the national stocks of natural gas for the country are summarised. Such measures aim to achieve the following goals: ensure a high level of filling of the stocks for the winter 2022–2023 as well as quickly diversify the supply of imported natural gas. In that, the Italian Government plans also aims to: a) widen the natural gas infrastructures by means of a new regasifier (still to be located and put in action); b) substitution of about 30 billion of natural gas from Russia by means of a diversification with other suppliers (25 billion cubic meters), c) further development of renewable sources along with the adoption of energy efficiency measures (5 billion cubic meters).

The Plan also promotes measures related to responsible and smart behaviours of citizens to decrease the consumption of natural gas and electricity. These measures include dissemination campaigns to suggest a set of virtuous behaviours by citizens, that could have immediate benefits in the reduction of the demand of natural gas and related

¹ The behaviors that the Government is promoting are about the reduction of the temperature and duration of showers, the use for winter heating of electric heat pumps used for summer air conditioning, lowering of the fire after boiling and the reduction of the oven ignition time, the use of a fully loaded dishwasher and washing machine, the disconnection of the powering of washing machine when not are not in use, the shutdown or insertion of the low-power function of the refrigerator when households are in vacation, the avoidance of the “stand by” mode for the TV, decoder, DVD, the reduction of the hours of switching on the bulbs.

economic costs, also contributing to the decarbonization policies.²

1.3. Planning just energy and circular economy transitions

The circular economy (CE) transition is a non-negligible challenge for the energy sector (Janik et al., 2020), strictly connected to the Green Deal and the EU climate goals (Pastore et al., 2022), via the promotion of a better use of natural resources and their diversification (Ghisellini et al., 2021). The CE transition integrates the renewable energy transition, considered as a necessary and useful step to promote more sustainable, resilient (Mulvaney et al., 2021; Ghisellini and Ulgiati, 2020) and hopefully just (Levenda et al., 2021; United Nations, Goal 7 Affordable and Clean Energy, 2022) economies and societies. Some scholars point out that the global crises of ecological degradation and social injustice are strictly interrelated and underline the importance to critically examine the values and narratives of the current economic and social systems and affirm the moral necessity of a socially just approach to the ecological crisis (Solomonian and Di Ruggiero, 2021; Carley and Konisky, 2020). In this regard, the innovative “doughnut economy” concept developed by Kate Raworth (2017) calls for a much needed “safe and just space for humanity”. Political leaders in the EU are also increasingly aware of the need for addressing the theme of environmental and social justice in energy (European Commission, 2021a) and CE transitions (European Commission, 2021b), in an attempt to ensure that the changes generated by both transitions in all the sub-systems of the society (cultural, legislative-political, economic-productive, technical-technological) are just for all the social groups and implemented through participative approaches without discriminations (Gebeyehu et al., 2019).

1.4. Goals and novelty of this research

The goal of this study is the assessment of energy costs and LCA environmental impacts of a real “Plan of the Italian Government” to face the present worldwide gas-shortage after the Russia-Ukraine war and the “Italian Long-Term Strategy for the Reduction of Greenhouse Gas Emissions”, with reference to the total electricity generated per year. As a comparison, we also evaluated the environmental impacts of selected scenarios modelled by the Lappeenranta-Lahti University of Technology and Green European Free Alliance³ for Italy and EU countries (Ram et al., 2022). Evaluating Italian plans and EU level scenarios allows to focus on options that take into account the actual EU mixes and the existing (economic, political, technological) constraints that affect the viability of scenarios beyond theoretical and good will proposals, which most often disregard aspects that are not easy to overcome in a short time. One of the novelties of this study is applying the LCA and its well-known methodological framework in this situation of emergence in evaluating the environmental performances of the Italian Governmental scenario and its evolution to 2030 and comparing them with other research scenarios aligned with the European decarbonization targets. To the best of our knowledge, there are not LCA studies that performed this assessment for which we also think there is an academic and Governmental need of building assessment frameworks useful to face this situation but at the same time do not disregard the existing and urgent environmental and social challenges.

This study also considers and compares two different approaches to the electricity production and related environmental impacts.

² Green European Free Alliance is a political group in the European Parliament that aims to make Europe a global leader in environmental protection, peace and social justice, fair globalisation, protection of human rights, available at: <https://www.greens-efa.eu/en/who-we-are> (last accessed: 13/12/2022).

³ <https://www.gse.it/servizi-per-te/news/fotovoltai-co-pubblicato-il-rapporto-statistico-gse-2021>.

- (i) Assessment of energy cost and LCA environmental impacts of electric productions from single sources (e.g.: natural gas, nuclear, wind, etc, see Table 3, based on literature studies), in order to explicitly ascertain their energy efficiency (electric output/cumulative energy input) and the midpoint & endpoint impact efficiency, per unit of electricity generated (kWh). This single source assessment allows to identify the strengths (e.g.: less GHG emissions, less non-renewable energy input) and weaknesses (e.g.: more ionizing radiations, more toxicity) of each energy production technology, on the basis of a multidimensional set of indicators, in order to suggest potential improvements within the specific production pattern itself (e.g.: improving plant technology, using recycled materials, recycle waste heat into the plant itself, etc);
- (ii) Assessment of energy costs and LCA environmental impacts of BAU energy mix in Italy and for a set of virtual scenarios where fractions of BAU production mix are replaced by equivalent fractions of a different production source, in order to evidence the fraction of energy and environmental benefits achievable (and additional costs, if any) through replacement. In so doing, focus on mix changes allows to compare replacement solutions based on their real LCA benefits, without disregarding costs, and finally compare the virtual scenarios to the BAU energy mix, per unit of electricity generated (kWh). This answers to most often suggested single-benefit “solutions” (e.g., less GHG or country’s energy dependence upon abroad imports), by identifying a multi-dimensional performance of each proposed energy mix and the potential consequences of energy policy changes. This is one of the novelties of this study compared to the existing literature.

A further novelty, compared to the literature, is the inclusion in the research context of the LCA of the just energy and CE frameworks as briefly presented in sub-section 1.3. Therefore, the results of the LCA will be interpreted and discussed in the lights of these two frameworks.

As a consequence, this study is organised as follows: Section 2. Materials and Methods analyses the previous literature, the goal of the present research and its novelty in terms of contribution to fill the current research gaps as well as the LCA approach. In particular, Sub-section 2.1 provides a short overview of the literature, while sub-section 2.2 provides information about the annual electricity generated in the year 2021 in Italy and the share of each fuel used for such electricity (BAU, Business as Usual). Subsection 2.3 describes the features and assumptions of the alternative scenarios to the BAU current scenario (year 2021). Each scenario is based on a set of fuels that contribute to the generation of the two functional units selected for the present LCA: 1 kWh and total annual electricity.

In particular, the following two types of alternative scenarios to the BAU are evaluated.

- **Governmental Scenarios** based on the adopted Italian Government Plan for the years 2021–2023 (replacement by 14% of electricity from natural gas by means of renewables, coal and oil) and its projection to the year 2030;
- **Proposed Research-based Scenarios** with 30% of electricity from natural gas replacement by means of renewables, nuclear and energy efficiency measures, assuming the same electricity production as in the year 2021. As mentioned above, scenarios for Italy and the EU (referring to the years 2030, 2035, 2040) developed by the Lappeenranta-Lahti University of Technology (LUT) were also evaluated, all characterized by higher annual electricity generated and higher share of renewables.

All the modelled scenarios are structured as described in sub-section 2.4, while Subsection 2.5 provides details about the LCA approach. Section 3. Results presents the results in terms of environmental impacts in each Midpoint and Endpoint impact categories, according to the

RECIPE 2016 Impact Assessment method. Results are then discussed in detail in Section 4. Discussion. Subsection 4.1 analyses and compares the environmental performances of the different scenarios and whenever possible some results are compared with the available literature. In subsection 4.2, results are discussed taking into account their implications to the just energy and circular economy frameworks while Section 5. Conclusions and Policy Implications summarizes the main general achievements and the theoretical and practical implications of the study.

Table 1 presents the list of acronyms used throughout this study and their meaning.

2. Materials and methods

The sub-section 2.1 provides a short overview of literature about LCA use to study energy and circular economy transitions. The following subsections 2.2, 2.3 and 2.4 describe the data used for the evaluation of the current electricity production in Italy and other Italian and EU scenarios. Finally, sub-section 2.5 deals with the main stages and features of the LCA approach applied to the present study. LCA performances (efficiency and impacts) of one-source electricity generation processes (to be used for mix scenario calculations) are shown in Table 3.

Fig. 1 summarizes the flows of information and data used as Materials and the stages of the LCA (Methods section) and achieved results in terms of Midpoint and Endpoint Indicators, reflecting environmental and social impacts generated by the analysed Italian and European electricity mix scenarios.

2.1. A short literature overview of life cycle assessment use for the evaluation of environmental sustainability of energy and circular economy transitions

The LCA approach has been widely used to evaluate the environmental sustainability of electricity mixes of countries worldwide (Gargiulo et al., 2020; Murphy and Raugei, 2020; Ramirez et al., 2020; Raugei et al., 2020; San Miguel and Cerrato, 2020; Carvahlo et al., 2022; Meng and Asuka, 2022) contributing to measure quantitatively and according to a holistic approach their environmental soundness in the whole life cycle of electricity generation, also preventing environmental burden shifts from one stage to another (Ramirez et al., 2020). LCA is an essential tool, of course not the only one, to evaluate on a scientific basis (avoiding greenwashing) the transition to CE in production sectors (including electricity) and the successful adoption of its principles in the economy and society (Mannan and Al-Ghamdi, 2021; Barros et al., 2020; Longo et al., 2020; Ncube et al., 2021). The CE model redefines the concept of value of products starting from process design to the end-of-life of products, with the feedback of materials and components to a new production cycle, through a deep analysis of the environmental, economic and social sustainability of products (Mannan and Al-Ghamdi, 2021). Gargiulo et al. (2020) suggest the need for adequate LCA

Table 1
Acronyms and their full terms.

| CE | Circular Economy |
|-------|--|
| EU | European Union |
| LCA | Life Cycle Assessment |
| BAU | Business As Usual |
| S-LCA | Social Life Cycle Assessment |
| DALY | Disability Adjusted Life Years |
| LUT | Lappeenranta-Lahti University of Technology |
| GHGs | Greenhouse Gases (emissions) |
| INECP | Integrated National Energy Climate Plan of Italy (to the year 2030) |
| EUREF | European Union Reference (Scenario) 2016 for energy, transport and GHGs emissions with trends to 2050. |
| PV | Photovoltaic (Solar) |
| GWP | Global Warming Potential |
| LFI | Life Cycle Inventory |
| IEA | International Energy Agency |

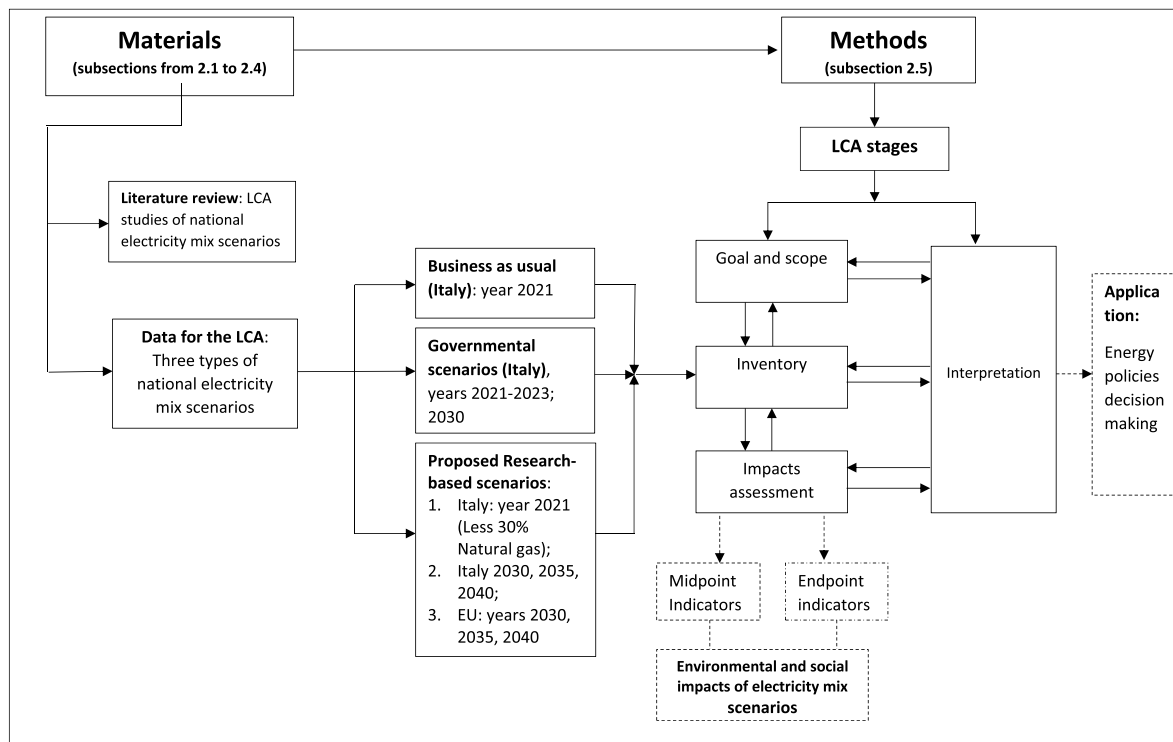


Fig. 1. Overview of the main content and stages of the materials and method sections of the present study.

accounting of the recycling scenarios in energy transition technologies, such as PV modules, in order to reduce the burdens on mineral resource depletion as well as improve the inventory data of their life cycle.

The LCA importance as a suggested key method for the assessment of environmental impacts of products or services in European legislations and policies increased over time since the first regulations (Sala et al., 2021), until recently with the development of the CE and the adoption of the Circular Economy Action Plan (European Commission, 2020). It is rather remarkable that one of the first applications is the Ecolabel Regulation where the life cycle thinking concept and LCA approach were suggested as suitable impact assessment framework for awarding the Eco-Label to processes and products. By identifying the main hotspots (local, regional and global) in the life cycle of a product or a service (Sala et al., 2021), LCA facilitates the link with the environmental dimension of products or services and their social dimension (Ingrao et al., 2021). When used in combination with s-LCA (social life cycle assessment, Kaiser et al., 2022) LCA reinforces the comprehensiveness of the analysis and the robustness of results (Ramirez et al., 2020). Within the CE framework, the Ellen MacArthur Foundation (2022) suggests the use of LCA in support to the CE transition for particular cases, by taking into account its limitations (e.g., LCA ignores impacts that are difficult to measure or not yet well known, may have the limited scope of the specific investigated system, and depends on the quality of the data and the assumptions made). Main LCA results may be the highlighting of hotspots and areas of improvement, testing against external factors changes (e.g., changes in the energy mix), comparison of environmental performances of two different materials packaging choices, later stages of the development of innovations when good and less uncertain data become available.

Several articles in the international LCA literature assessed the decreasing environmental impacts of the transition to electricity mix scenarios consistent with decarbonization plan and targets (Table 2). Most studies evidence the reduction of GHGs emissions and water footprint (Meng and Asuka, 2022) as well as water availability, in particular in the case of relevant share of hydroelectricity (Ramirez et al., 2020), in so confirming the need to consider the energy-water

nexus in energy policies. Other factors (population growth, increasing/decreasing energy demand by society, climate change uncertainties, future scarcity of oil sources, lack of change in the lifestyle, etc.) are also relevant and could affect the future decarbonization patterns and performances (San Miguel and Cerrato, 2020; Ramirez et al., 2020) and in some cases more than offset in a negative way the final results of national energy policies, leading to an increase of the contribution to GWP (Ramirez et al., 2020). Ambitious political commitment towards renewables is a key factor for the success of future decarbonization scenarios (Murphy and Rauegi, 2020; San Miguel and Cerrato, 2020).

Rauegi et al. (2020) assess the environmental impacts of the so-called “Future Energy Scenario - 2°” that is one of the decarbonization pathways to the year 2050 for United Kingdom that foresees electricity generation capacities for all the grid mix technologies and the associated annual electricity generation over the next 30 years. Their results show the importance of the adoption of a life cycle approach for the identification of the sources with the most relevant impacts in the production of electricity as well as the LCA usefulness for improving their environmental performances or alternatively encourage their replacement with other sources. Finally, concerning the share of nuclear in the mix, the authors point out that the continued and even increased share expected after 2030 poses challenges in the energy transition of UK increasing its energy dependence from abroad, given that UK lacks of domestic uranium ores.

With regard to Italy, two recent LCA studies (Gargiulo et al., 2020; Carvahlo et al., 2022) analysed the evolution of the energy mixes and impacts of the electricity Italian mix from baseline scenarios to 2030 scenarios. Gargiulo et al. (2020) point out that the generation of 1 kWh of electricity in the 2030 scenarios (base 2030, INECP 2030 and EUREF 2030) shows a reduction of the environmental impacts in all the selected impact categories with the lowest environmental impacts in the 2030 INECP scenario for almost all the impact categories. The contribution to climate change from the current scenario 2016 to the 2030 INECP scenario decreases by 46%. The results, show a decrease of ionizing radiation impacts in both 2030 scenarios (2030 BASE and 2030 INECP)

Table 2
Recent Life cycle assessment studies published in the international literature.

| Author/s | Method/s | Goal of the study | Country | Further results | Functional Unit |
|--------------------------|-----------------------------|---|----------------|---|---|
| Carvahlo et al., 2022 | LCA | Comparison of the evolution of the environmental impacts of the Italian electricity mix from 2018 to 2030 with that of other European countries: Belgium, Denmark, Finland, France, Germany, Portugal and Spain. | Italy | <ul style="list-style-type: none"> • Average reduction of 42% of the impacts to climate change in European Union countries investigated; • Adoption of INECP scenario for Italy should reduce by 50% the impacts to Climate Change performing similarly well as France and Portugal. | 1 kWh of Gross National Consumption of electricity plus the net electricity foreign exchange (imports of electricity minus exports of electricity). |
| Meng and Asuka, 2022 | Hybrid LCA | Evaluation of the impacts on carbon emissions and water consumption of the energy transition in Japan under the Sixth Strategic Energy Plan to 2030 compared to the year 2015. | Japan | <ul style="list-style-type: none"> • The energy transition will reduce the carbon emissions and increase the water consumption; • Decrease of acceptance of nuclear power after Fukushima accident; • The transition to 100% renewable electricity in Japan is possible. | Total electricity generated |
| Gargiulo et al. (2020) | LCA | Evaluation of the environmental impacts of two current scenarios (years 2016 and 2017) and three scenarios at 2030 (2030 Base, 2030 EU reference scenario for Italy and 2030 INECP (Italian Integrated National Energy and Climate Plan). | Italy | <ul style="list-style-type: none"> • Reduction of the environmental impacts in all the selected impact categories for the generation of 1 kWh of electricity in the three 2030 scenarios; • 2030 INECP has the lower impacts than the other scenarios except for mineral, fossil & renewable resources depletion, due to the increase of solar PV share; • Normalized values of ionizing radiation and climate change decrease from the current scenario (2016) to the 2030 scenario, while the normalized values of mineral, fossil & renewable resources depletion increase from about 0.10 to about 0.18 in the 2030 INECP scenario. | 1 kWh of Gross National Consumption of electricity plus the net foreign exchange (imports of electricity minus exports of electricity). |
| Murphy and Raugei (2020) | LCA and Net Energy Analysis | Evaluation of the changes in net energy, life cycle energy and GHGs emissions of electricity generated in New York due to the energy transition. Calculation of the following indicators: EROI and net-to-gross energy ratios, CED and GWP. Clen Energy standard of New York set the target 70% renewable energies generation by 2030 and 100% by 2040. | US (New York) | <ul style="list-style-type: none"> • The achievement of a grid mix as per the target of 70% of electricity from renewables will strongly reduce the GHGs emission per kWh; • Renewable technologies have a lower CED than conventional thermal technologies (steam turbines, combined cycles and nuclear reactors). | 1 kWh of electricity generated by the grid mix. |
| Ramirez et al. (2020) | LCA | Assessment of Environmental impacts of electricity generation from year 2012–2018 and forecasting electricity scenarios from 2020 to 2050. | Ecuador | <ul style="list-style-type: none"> • Hydropower (and in particular run-on-river) has very low impact compared to electricity from fossils. Increasing hydro share in the mix strongly reduces the impacts; • The evolution of the impacts depends on the share of electricity from hydro; • The expected increase of the electricity demand to 2050 will more than offset the efforts in increasing the share of renewables in the electricity mix; • Water-energy nexus should be taken into account due to climate change effects on water availability for hydro; • Many factors beyond decarbonization affects the transition to sustainability. | 1 kWh of net electricity supplied to final consumers. |
| Raugei et al. (2020) | Net energy and LCA | Assessment of the environmental and energy impacts of energy transition scenarios for the UK and analysis of the evolution of the environmental impacts as well as the net energy delivery in the shift from the current United Kingdom grid mix (year 2019) to a future mix in the so-called UK National Grid's "2°" scenario (years 2035 and 2050). | United Kingdom | <ul style="list-style-type: none"> • The study further confirms that the UK National Grid's "2°" mix is effective for decarbonizing UK electricity even if not to the extent projected; • Biogas and biogas showed a low return on energy investment. Biogas and biomass show a high contribution for the generation of 1 kWh of electricity to acidification potential compared to the other sources; • Large-scale development of renewable energy generation (wind, solar PV, tidal) entails some trade-offs in terms of depletion of metal resources and toxicity potential impacts. | 1 kWh of electricity delivered by the UK grid, inclusive of energy storage and transmission. |

(continued on next page)

Table 2 (continued)

| Author/s | Method/s | Goal of the study | Country | Further results | Functional Unit |
|------------------------------|--|---|---------|--|------------------------------------|
| San Miguel and Cerrato, 2020 | LCA, Levelized cost of electricity and direct life cycle employment generation (direct number of jobs) | Analysis of the evolution of sustainability of Spain's electricity system from 1990 to 2015 and future projections (2030 and 2050). The future scenarios consider the goals of the Spanish Renewable Energy Action Plan 2020, the European 2030 Climate and Energy Framework and the European 2050 long-term strategy. Analysed scenario are: current situation (2015) and four scenarios for the years 2030, 2050 (decarbonization, current policies, accelerated technology advance, stagnation). | Spain | <ul style="list-style-type: none"> The results are analysed across three time periods: 1990–2000: strong increase in the impacts from the electricity system in most of the environmental categories (CC, FDP, OLDP, TAP, HTP, PSP) due to economic growth and increase of energy demand and dependence on fossil sources in the mix; 2000–2008: less rapid increase of electricity demand mainly met by natural gas while the share of coal reduced, the effects of the change on economic costs and employment are low; 2008–2016: strong economic crises coupled with ambitious public strategies promoting the development of renewables. The factors lead to a reduction of GHG per kWh, a small increase of generations costs and a high increase of employment; The analysis of the future projected three scenarios (in particular in the year 2050) that have a higher share of renewables show a reduction of GHGs emissions per kWh, higher employment rates and lower economic costs. | 1 MWh; Cost (MM €); Number of Jobs |

Table 3
LCA Midpoint impacts per 1 kWh of the production of electricity from different sources.

| ReCiPe Midpoint (H) 2016 | Reference unit/ kWh | Oil plant | Average Nuclear Plant ^a | Average Nat-GAS ^b | Average PV Plant ^c | Hard Coal | Hydro | Wind onshore | Geothermal |
|---|------------------------|-----------|------------------------------------|------------------------------|-------------------------------|-----------|----------|--------------|------------|
| Fine particulate matter formation | kg PM2.5 eq | 2.37E-03 | 4.77E-05 | 5.61E-04 | 1.59E-04 | 1.81E-03 | 1.07E-03 | 5.53E-05 | 1.57E-04 |
| Fossil resource scarcity | kg oil eq | 2.81E-01 | 4.04E-03 | 2.60E-01 | 1.67E-02 | 2.26E-01 | 2.69E-01 | 6.45E-03 | 1.76E-02 |
| Freshwater ecotoxicity | kg 1,4-DCB | 1.80E-03 | 1.17E-03 | 1.93E-03 | 1.75E-02 | 1.29E-02 | 7.41E-03 | 1.95E-02 | 2.42E-03 |
| Freshwater eutrophication | kg P eq | 1.56E-05 | 6.11E-06 | 2.86E-05 | 5.48E-05 | 4.16E-04 | 1.36E-04 | 1.55E-05 | 1.43E-05 |
| Global warming | kg CO2 eq | 9.02E-01 | 1.62E-02 | 6.84E-01 | 6.57E-02 | 1.14E+00 | 9.01E-01 | 2.58E-02 | 6.27E-02 |
| Human carcinogenic toxicity | kg 1,4-DCB | 4.36E-03 | 2.22E-03 | 3.94E-03 | 6.06E-03 | 2.60E-02 | 1.15E-02 | 8.47E-03 | 7.59E-03 |
| Human non-carcinogenic toxicity | kg 1,4-DCB | 6.32E-02 | 3.10E-02 | 5.20E-02 | 2.47E-01 | 3.91E-01 | 1.63E-01 | 8.63E-02 | 5.68E-02 |
| Ionizing radiation | kBq Co-60 eq | 1.44E-02 | 1.17E+00 | 1.23E-02 | 1.02E-02 | 8.25E-03 | 1.45E-01 | 1.87E-03 | 2.76E-03 |
| Land use | m2a crop eq | 4.26E-04 | 1.47E-04 | 2.68E-04 | 3.90E-04 | 5.79E-03 | 1.78E-03 | 9.12E-04 | 2.69E-04 |
| Marine ecotoxicity | kg 1,4-DCB | 4.82E-03 | 1.72E-03 | 2.86E-03 | 2.30E-02 | 1.80E-02 | 1.04E-02 | 2.39E-02 | 3.23E-03 |
| Marine eutrophication | kg N eq | 5.00E-05 | 8.14E-06 | 1.76E-05 | 5.34E-05 | 4.45E-05 | 1.64E-03 | 1.06E-05 | 6.89E-06 |
| Mineral resource scarcity | kg Cu eq | 4.02E-04 | 8.84E-04 | 4.44E-04 | 1.37E-03 | 3.75E-04 | 1.42E-03 | 1.48E-03 | 1.62E-03 |
| Ozone formation, Human health | kg NOx eq | 2.86E-03 | 5.05E-05 | 1.03E-03 | 1.74E-04 | 2.20E-03 | 1.54E-03 | 7.58E-05 | 4.48E-04 |
| Ozone formation, Terrestrial ecosystems | kg NOx eq | 2.90E-03 | 5.15E-05 | 1.08E-03 | 1.81E-04 | 2.20E-03 | 1.57E-03 | 7.88E-05 | 4.57E-04 |
| Stratospheric ozone depletion | kg CFC11 eq | 6.21E-07 | 4.13E-08 | 3.26E-07 | 3.63E-08 | 2.77E-07 | 4.92E-07 | 1.08E-08 | 7.05E-08 |
| Terrestrial acidification | kg SO2 eq | 7.67E-03 | 8.08E-05 | 1.67E-03 | 4.04E-04 | 5.29E-03 | 3.08E-03 | 1.19E-04 | 3.09E-04 |
| Terrestrial ecotoxicity | kg 1,4-DCB | 3.13E+00 | 3.24E-01 | 1.13E-01 | 1.43E+00 | 3.25E-01 | 6.46E-01 | 2.44E-01 | 1.35E-01 |
| Water consumption | m3 | 2.30E-03 | 3.13E-03 | 1.05E-03 | 1.84E-03 | 1.88E-03 | 6.30E-03 | 3.29E-04 | 1.32E-02 |

^a Average values from BWR-CH, BWR-IN, BWR-RU, PWR-CH, PWR-FR, PWR-RoW.

^b Average values from Nat Gas-IT Conventional Power Plant, Nat Gas-RoW Conventional Power Plant and Nat Gas-RoW Comb Cycles Power Plant.

^c Average values from PV-IT 570kWp open ground multi S; PV-RoW, 3kWp flat roof multi S; PV-RoW 3kWp slanted roof multi S.

compared to the baseline 2016 scenario, due to the reduction of the imports of electricity from countries that produce electricity from nuclear source. The normalized LCA results also show that ionizing radiations, climate change and mineral, fossil & renewable resources depletion are the most affected environmental impact categories within the electricity mix of Italy.

Carvahlo et al. (2022) evaluated the environmental impacts of two scenarios (current, year 2018 and future, year 2030) for Italy and some European countries: Belgium, Denmark, Finland, France, Germany, Portugal and Spain modelled on the basis of EUREF and INECP for Italy and EUREF for the other European countries.

The results of the energy mixes evolution from 2018 to 2030 shows that there is a small foreseen increase of the electricity consumed in the year 2030 with all countries widening their share of electricity from wind while nuclear increases only in Finland and decreases its share in Belgium and Germany in favour of natural gas due to the phase-out of some nuclear plants. Coal remains stable only in Germany and decreases in the other countries. The results of the LCA impact assessment are consistent with the decarbonization path of the seven EU countries. From 2018 to 2030, Climate change worsens only in Belgium following the expected phase out of nuclear plants, while mineral, fossil & renewable resource depletion impact category increases in all countries due to the consumption of resources for nuclear, wind and solar plants and the imports of nuclear and wind electricity.

2.2. Current electricity mix scenario

The data of the current scenario (business as usual, BAU) have been retrieved from the database by TERNA (that is the main operator in Italy for the transmission of electricity in the country) and refer to the net electricity production of Italy in the year 2021, amounting to 280,045.2 GWh. The latter has been added to the net foreign exchange equal to 42,793 GWh in the year 2021 to obtain a total electricity generation of 322,838 GWh (TERNA, 2021a, b). Fig. 2 shows the net electricity production by type of fuel in the year 2021 and in the first group of assumed alternative scenarios (of course, total yearly production is not the same in all scenarios, depending on the assumption). In the BAU scenario, natural gas had the highest share in the net production of electricity of the year 2021 (44.3% of total electricity) while hydro (19.5%), solar PV (8%), wind (7.1%), hard coal (4.4%), other solid fuels (5.1%), other gaseous fuels (2.3%), geothermal (1.7%), other sources (0.2%).

The electricity demand of the country in 2021 has been met by 86.6% with national production and the rest (13.6%) by means of imports of electricity from other countries (France, Switzerland, Slovenia, Montenegro, Greece and Austria) (TERNA, 2021a, b). At the end of the year 2021, the electricity produced from renewables amounted to 115 TWh with solar PV contributing with a share of about 22%, following hydro which is the main renewable source at 39% (GSE, 2022).⁴

Concerning wind energy, in the year 2021 Italy installed about 0.3 GW of new plants reaching a total capacity of 11.1 GW. Compared to some European countries Italy still performs worse in terms of wind power and installed capacity. In the same year, UK added a new capacity by 2.6 GW and Sweden increased by 2.2 GW.⁵ At worldwide level the new installations have increased by 13% in the year 2021 compared to the year 2020. Just as a comparison, although considering the different size and population, China added a new capacity from wind by 55.8 GW achieving a total of 344 GW at the end of the year 2021 (World Wind

⁴ Germany installed a new wind capacity by 1,7 GW (total wind capacity is 64 GW), France by 1,1 GW (total capacity is 19 GW), Denmark by 0,9 GW (total capacity is 7,1 GW), Spain by 0,7 GW (total capacity is 28,1 GW) while Greece installed 0.3 GW.

⁵ European Platform on Life Cycle Assessment, Life Cycle Assessment, available online at: <https://eplca.jrc.ec.europa.eu/lifecycleassessment.html> (last accessed: 29/12/2022).

Energy Association, 2022).

2.3. Governmental and proposed research-based electricity mix scenarios less dependent on natural gas

Besides the business-as-usual scenario (year 2021), the present study considers a further scenario modelled on the basis of the data of the electricity mix of the year 2021 and the measures of the “National Plan for the containment of natural gas consumption” (Ministry of Ecological Transition, 2022). The Plan of the Italian Government suggests the substitution of 2.1 cubic meters of natural gas in the period 1 August 2022–31 March 2023 for the production of electricity with other conventional fuels such as coal, oil and bioliquids. The Plan also forecasts an increase of the capacity of production of electricity from renewables (solar PV and wind) equal to 8 GW from 2023 onwards. The production of electricity with conventional fuels and the additional renewable power from 2023 (8 GW) should replace about 14.2% of the total amount of electricity produced from natural gas. For the sake of simplicity, we assumed a Government Plan scenario for the year 2023 based on the data of the total electricity generation (322,838 GWh) of the year 2021, with a reduction of 14.2% of electricity from natural gas and its substitution with coal, oil and renewables.

We also investigated further research-based scenarios where we assumed a replacement by 30% of the amount of electricity from natural gas with (i) only wind, (ii) only solar PV, (iii) only nuclear, (iv) only energy savings measures and finally (v) a scenario where these four options replace 30% of electricity from natural gas. The scenarios are more advanced in terms of natural gas substitution and allow to appreciate the environmental contribution due to the replacement of each one of the sources with natural gas. Moreover, one of these scenarios evaluates the environmental impacts due to the possible introduction of nuclear source in the electricity mix. Fig. 2 shows the electricity mix of Italy in all these described scenarios on the basis of the data of the year 2021. The total amount of electricity generated in scenarios 1, 2, 3 is the same as the BAU scenario and that of Government Plan (322,838 GWh). In scenario 4 the total amount of electricity is 280,159 GWh (due to the proposed substitution by 30% of electricity from natural gas with energy efficiency measures) while in scenario 5 is 312,168 GWh as 30% of electricity from natural gas is replaced by increasing the share of wind, solar PV, nuclear and energy efficiency measures of the same amount.

2.4. Governmental and proposed research-based scenarios for the years 2030, 2035 and 2040

The present study also modelled the scenario for the year 2030 of the “National Plan for the containment of natural gas consumption” of the Italian Government on basis of the BAU scenario described in the previous section. We assumed a constant net electricity production equal to the year 2021 (322,838.2 GWh) and the development of renewable energies of 8 GW per year from 2023 to 2030. This would add a new renewable capacity of 64 GW in the year 2030 distributed between solar PV (51.2 GW) and wind (12.8 GW). In the year 2030, a yearly electricity production from solar PV of 71,680 GWh and from wind of 22,211.76 GWh should be achieved on the basis of the current development of such two sources.

As a comparison, we also evaluated three proposed research-based scenarios both for Italy and EU (years 2030, 2035, 2040) modelled by LUT University and Greens European Free Alliance (Ram et al., 2022). In these scenarios, solar PV and wind are considered the main sources for the production of electricity as can be seen from Fig. 3 both for Italy and EU.

The construction of new nuclear plants is not considered in all the scenarios due to high costs and long times that are not competitive to those of renewable sources. However, for the EU, the contribution of nuclear to the production of electricity remains until the phasing out of

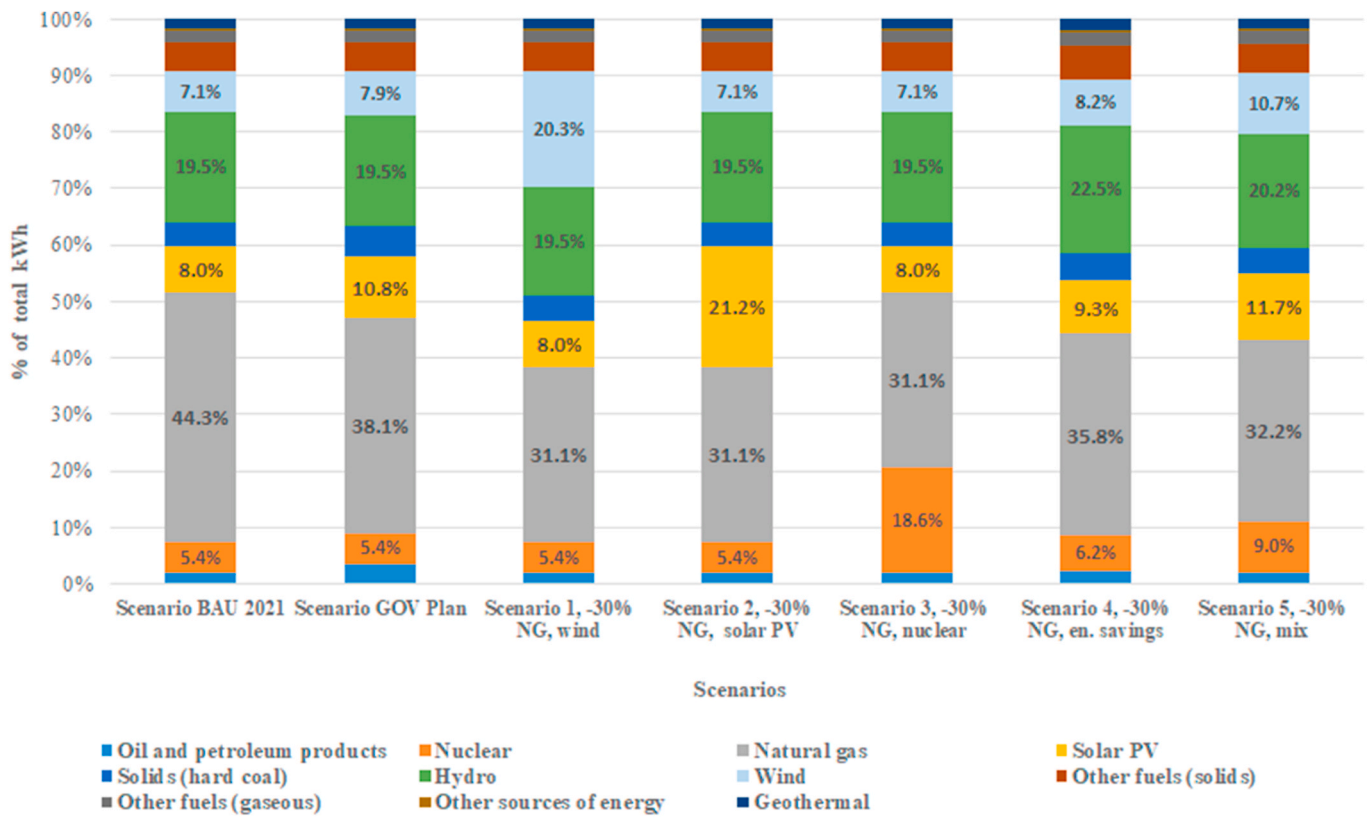


Fig. 2. Net electricity production by fuel in the BAU scenario, GOV Plan scenario and five proposed research-based scenarios. Elaboration of the authors with data by TERNA, 2021c. In BAU and GOV Plan scenarios and scenario 1, 2, 3 the total electricity generated is 322, 838 GWh. In scenario 4 the total electricity generated is 280,159 GWh while in scenario 5 the total electricity generated is 312,168 GWh.

the existing plants. These scenarios also characterize themselves for a high increase of electricity generation compared to the current BAU scenarios both for Italy (322.84 TWh) (TERNA, 2021a,b) and the whole EU (2664 TWh) (EUROSTAT, 2020). At the year 2030 the expected electricity generation for Italy would almost double achieving 432.39 TWh (scenario Italy 2030) and increasing to 694.13 TWh in the year 2035 (scenario Italy 2035) and reducing to 478.64 TWh in the year 2040 (scenario Italy 2040). About the EU, projected electricity generation to 2030 is 3746.1 TWh (scenario EU 2030), while 6361.52 in the year 2035 (scenario EU 2035) and 4237.71 TWh (scenario EU 2040) in the year 2040.

These scenarios, hereafter defined as “smarter”, align with the decarbonization goals of the EU to the year 2050 that aim to reduce the amount of Greenhouse Gas Emission by 80–100% compared to 1990 levels (European Union, 2021). In turn, these scenarios for Italy, are also in line with the “Italian Long-Term Strategy for the Reduction of Greenhouse Gas Emissions” (hereinafter the Strategy) that is the proposed plan for decarbonization paths for Italy in order to reach, by 2050, the so-called “climate neutrality” (Ministry of Environment, Protection of Territory and the Sea et al., 2021). The latter is a condition of balance between emitting carbon and absorbing carbon from the atmosphere in carbon sinks with net GHGs emissions equal to zero that are counterbalanced by carbon sequestrations sources (European Parliament, 2022b). The Strategy takes as a reference the Integrated National Plan for Energy and Climate adopted to achieve the first step in the decarbonization path for Italy for the period 2021–2030. This plan has identified specific goals about the growth of renewable sources (30% in final consumption), the improvement of energy efficiency (−43% compared to the trend scenario) and the reduction of GHGs in the “Emission Trading System” and “non-Emission Trading System” sectors (respectively at least −43% and −33% compared to the amount of the

year 2005).

Finally, the Strategy also evidences that the emissions in terms of CO₂/kWh and CO₂ eq/kWh reduced over time by 40% compared to the year 2005 thanks to the contribution of renewables in the electricity mix. These latter have grown from 20 GW to 55 GW in the period 2004–2018 with a strong increase in particular from the year 2010 onwards. The projections to the year 2050 expect a radical transformation of the electricity system that would further expand its share in the whole energy consumption of the country, due to the use of electric energy for the production of hydrogen and electric fuels, the generation of heat without CO₂ emissions, the application of advanced system for direct capture of CO₂ from the atmosphere. In order to meet the decarbonization goals the Strategy expects an increase to the year 2050 of the electricity demand of about 650 TWh. In the year 2050, the electricity generation should almost be entirely sourced by renewables with a minimal share from natural gas integrated by capture and storage systems of CO₂. A high contribution is expected by solar PV power that should rise of about ten times the current levels while wind will grow up to 40–50 GW and geothermal, wave and tidal energy will contribute more than the current levels.

2.5. The life cycle assessment approach

Life cycle assessment, also called environmental LCA, is a well-known methodology regulated by the standards ISO 14040:2006/AmD 1:2020) that allows the quantification of the potential environmental impacts of a product, process, activities in all the life cycle stages from raw materials extraction to end of life including the reintroduction of the materials/components into a new production/consumption cycle (Muralikrishna and Manickam, 2017).

The LCA has been applied through its main four stages: goal and

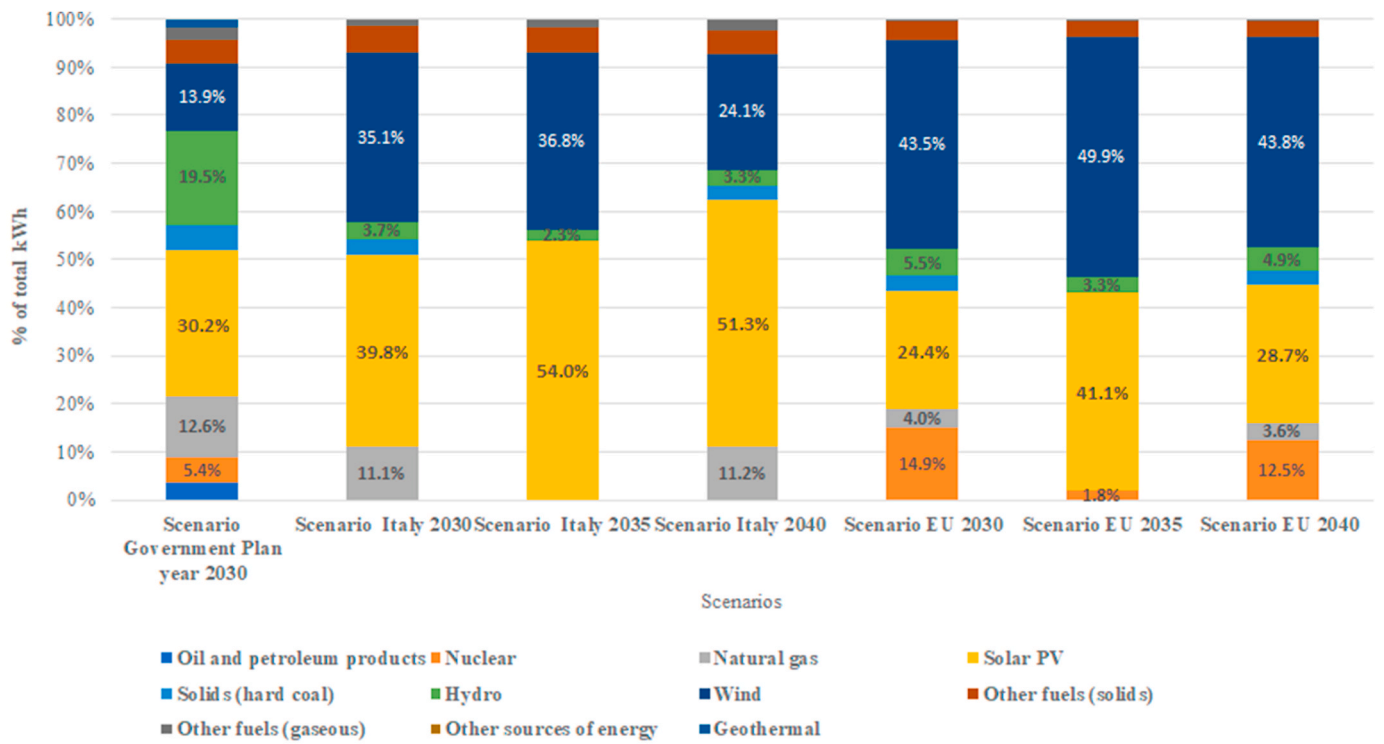


Fig. 3. Electricity generation by fuel in the Government Plan in the year 2030 and in proposed research-based scenarios for Italy and European Union modelled by LUT University and Greens European Free Alliance (Ram et al., 2022). In the 2030 Government Plan scenario the total electricity generated is 322, 838 GWh. In the Italy 2030 scenario the total electricity amounts to 432, 403 GWh while in the scenarios Italy 2035 and Italy 2040 it is 694,126 GWh and 478,656 GWh respectively. In the EU 2030 scenario the total electricity produced is 3,746,112 GWh while in the EU 2035 and EU 2040 scenarios it is 6,361,536 GWh and 4,237,654 GWh respectively.

scope, life cycle inventory analysis, life cycle impact assessment and life cycle interpretation (Fig. 1). These latter are described next in the light of the characteristics of the present study.

2.5.1. Goal and scope

This stage is fundamental in an LCA study, to clearly define goals, motivations, the intended application of results and the recipients to which the results will be communicated. The choices related to these aspects strongly affect the whole study and its level of detail in terms of boundaries of the system and processes to be included within such boundaries.⁶ This is why the Fig. 1 shows that some of the stages of the LCA (inventory, impacts assessment and interpretation) are highly interdependent with the first stage. This LCA has the following main goals.

- Evaluation and comparison of the potential environmental impacts of the different electricity production mix scenarios for Italy summarised in the previous sub-sections 2.2 and 2.3 as well as comparison with selected EU smarter electricity scenarios (sub-section 2.4);
- Identification of the potential environmental costs and benefits of each scenario;
- Evaluation and interpretation of the results of this study on the basis of a just energy and circular economy transition frameworks;

The results of this LCA are expected to provide useful scientific data in support of stakeholders and policy makers decisions, within the energy sector, the Italian Government and European Commission.

The functional units are, depending on the case, the production of 1

⁶ LCIA: ReCiPe 2016 <https://www.rivm.nl/en/life-cycle-assessment-lca/recipe>.

kWh of net electricity and the total net electricity use (kWh) in the year 2021 in Italy, also including the net foreign exchange in the same year. The scope includes boundaries, the present debate about different energy policy options, as well as the European energy mix and imports from outside Europe.

The system boundaries of this LCA are cradle to grave for the different electricity generation systems (thermoelectric, nuclear and renewable) and include raw materials extraction and fuels supply, construction and plant operation, end-of-life disposal for thermoelectric plants, hydroelectric, solar PV and wind power plants. About electricity from nuclear energy the end-of-life stage does not include the environmental impacts of the disposal of radioactive waste in temporary and final repositories (sometimes only including transport and storage site preparation). This is because in general the low and medium radioactive waste is stored in proximity of the power plant itself, while the highly radioactive waste is treated for different purposes (including military) and partially returned to temporary repositories (Ulgiati and Ghisellini, 2013). Actually, a permanent nuclear waste repository does not exist, after several failed options worldwide (Bell and Farlaine, 2022; O’Leary, 2022).

2.5.2. Life cycle inventory (LCI)

The second LCA stage accounts for the input and output flows of an investigated product-system from and to the natural environment. In the LCI, the input flows are about materials and energy extracted from the environment and then transformed in the system while outputs are the emissions and waste of the system released to the environment (Mohan, 2018).

This LCA uses primary data about the net electricity generation in Italy in the different scenarios (BAU, Government Plan, Scenarios 1 to 5 assuming a 30% reduction of electricity from natural gas), while secondary environmental data (that generally are previously published

data about the unit impacts generated by the processes) are derived from the Ecoinvent Database 3.1 (Table 3). The environmental data retrieved from the Ecoinvent Database 3.1 consider different type of plants (and reactors, in case of nuclear) for the production of electricity (thermal, nuclear and renewable), in order to represent all the types of available plants in Italy and abroad (e.g. imported nuclear electricity). Data from Table 3 provide a better picture of the performance (efficiency and impacts) of electricity production from each different source, in order to understand if a source is suitable to be part of the mix and what is its improvement potential. Table 3 reports the environmental data about the impacts of the production of 1 kWh, calculated as weighted averages of LCA midpoint impacts of individual sources from the Ecoinvent Database version 3.1 adjusted to the investigated countries. For example, in the case of nuclear electricity the weighted averages of LCA midpoint impacts derive from considering the individual midpoint impacts of six types of nuclear plants located in different areas (BWR-CH, BWR-IN, BWR-RU, PWR-CH, PWR-FR, PWR-RoW). The weighted average of LCA midpoint impacts related to each type of plant and source have been multiplied by the specific share in the electricity Italian or EU mixes in order to obtain the LCA impacts per FU: 1 kWh and total kWh produced annually. Here we report only Table 3 with the environmental data about the LCA midpoint impacts. We also collected the environmental data about the impacts of the production of 1 kWh from the Ecoinvent Database 3.1 and calculated the weighted averages of LCA endpoint impacts for each individual type of plant and source.

Secondary data have been also used for the electricity generation in Italy and EU to assess the impacts of 2030, 2035 and 2040 scenarios modelled by LUT University and Greens European Free Alliance (Ram et al., 2022). The associated environmental data have been retrieved from the Ecoinvent 3.1 Database.

For Biofuels and Biogas, the Ecoinvent database does not provide the impacts for these sources. Therefore, we have used the same impacts of fossil oil as conservative estimates.

2.5.3. Life cycle impact assessment and interpretation

In this stage, the secondary environmental data from the Ecoinvent Database 3.1 concerning the processes for the generation of electricity from the different types of fuels (natural gas, oil, coal, nuclear, wind, hydro, solar PV) have been elaborated by means of the software OpenLCA 1.10 (<https://www.openlca.org>) and the impact assessment methods Recipe Midpoint and Endpoint (H) 2016 in order to determine the contribution of each kWh and total country kWh produced from the different fuel types to the environmental impact categories. Fig. 4 shows the Midpoint impact categories considered in this study and their relation with the Endpoint impact categories. Midpoint impact categories are focused on single environmental impacts while Endpoint impact categories result from aggregating the environmental impacts within three areas of potential damage: damage to human health (unit of measure: DALY as Disability Adjusted Life Years (DALY) measuring the impact of premature death, disease or disability of population, due to environmental pollution; damage to ecosystems (unit of measure: Species richness lost per year) and damage to resource availability (unit of measure: US \$) as the increased costs due to the future extraction of minerals and fossil fuels.⁷ The secondary data from Ecoinvent Database 3.1 have been jointly processed with the primary data in order to obtain the environmental impacts of 1 kWh and total kWh produced on the basis of the Italian and EU electricity mix under the different scenarios. The results of the impact assessment stage are presented in the next Section 3 and interpreted and discussed in the light of the goal of this study in Section 4.

⁷ Disability Adjusted Life Years (DALY) quantifying the impact of premature death or disability that climate change has on the population.

3. Results

This study presents the results with reference to two Functional Units: 1 kWh of net electricity generated and total annual net electricity generated (total kWh) in Italy or EU. In the first case (1 kWh), the results point out the specific environmental performances (impact generation efficiency) of the investigated scenarios for electricity production, while, in the second case (total electricity), they help create a global relationship of each scenario with the size and characteristics of the system (namely population, economy, and surrounding environment as a whole), in order to understand if the system can afford the investigated electric production. Furthermore, some scenarios refer to the years 2021–2023 (BAU and Governmental) and others at 2030–2040 (Governmental and research scenarios), in order to ascertain how the energy situation in Italy could evolve over time, compared to that in Europe.

3.1. Environmental impacts per 1 kWh of net electricity generated

Table 4 shows the environmental impacts to the 18 midpoint impact categories generated by the production of 1 kWh of electricity in the seven scenarios for Italy 2021–2023, involving different shares of some fuels (natural gas, solar PV, wind) used for generating electricity in the mix. The scenarios are: business as usual (BAU, year 2021), the Governmental Plan scenario (year 2021–2023) decreasing by about 14% the electricity produced from natural gas, and five scenarios assuming a reduction of 30% of electricity from natural gas and its replacement by wind, solar PV, nuclear, energy savings measures and a mix of all these four options, as described in Fig. 1.

Table 4 indicates that the production of 1 kWh of electricity releases 0.62 kg CO₂ eq in the BAU scenario, not very different than 0.60 kg CO₂ eq expected in the Government Plan scenario. In the other scenarios (except scenario 4) the impacts to Global Warming are lower as 1 kWh generates 0.53 kg CO₂ eq (scenario 1 and 3), 0.54 kg CO₂ eq (scenario 2) and 0.55 kg CO₂ eq (scenario 5) respectively. With regard to the other impact categories, the contribution to terrestrial acidification worsens in the Government Plan scenario (2.30E-03 kg SO₂ eq/kWh) and Scenario 4 (2.30E-03 kg SO₂ eq/kWh) compared to the BAU scenario (2.22E-03 kg SO₂ eq/kWh), while it decreases in the others reaching the lower values in scenario 1 and 3 (2.01E-03 kg SO₂ eq/kWh). It is worth pointing out that the contribution to ionizing radiation in scenario 3 is the highest (0.25 kBq Co-60 eq/kWh) compared to the other scenarios (0.10 kBq Co-60 eq/kWh) including the BAU, the Government Plan, and scenarios 1 and 2.

The environmental impacts to the Endpoint impact categories of the analysed seven scenarios differ much for 1 kWh of net electricity produced shifting from the BAU and Government Plan scenarios to the others for the category DALY (Table 5) while in a lower extent for the other two categories (species*year and USD 2013). Scenario 3 resulted with the lower Endpoint impacts for the production of 1 kWh of electricity that affects human health by 9.72 E+07 DALY (Disability Adjusted Life Years) as well as species diversity by a potential 2.14E-09 Species*yr decrease and the economy by an increased cost equal to 5.82E-02 USD 2013.

Table 6 shows the midpoint impacts of the production of 1 kWh in the Government Plan 2030 scenario as well as in all the supposedly smarter scenarios for Italy and EU from 2030 to 2040. Overall, the impacts to many categories in the 2030 Government Plan scenario are higher than the other scenarios for Italy 2030 to 2040 as well as for the EU scenarios 2030 to 2040. Concerning the specific contribution to Global Warming, the 2030 Government Plan scenario releases 0.44 kg CO₂ eq/kWh while much less GHGs emissions are estimated in the smarter scenarios for Italy to 2030 (0.24 kg CO₂ eq/kWh), 2035 (0.12 kg CO₂ eq/kWh) and 2040 (0.24 kg CO₂ eq/kWh) as well as in EU 2030 (0.18 kg CO₂ eq/kWh), 2035 (0.10 kg CO₂ eq/kWh) and 2040 (0.16 kg CO₂ eq/kWh) scenarios. The ionizing radiation impacts are lower for

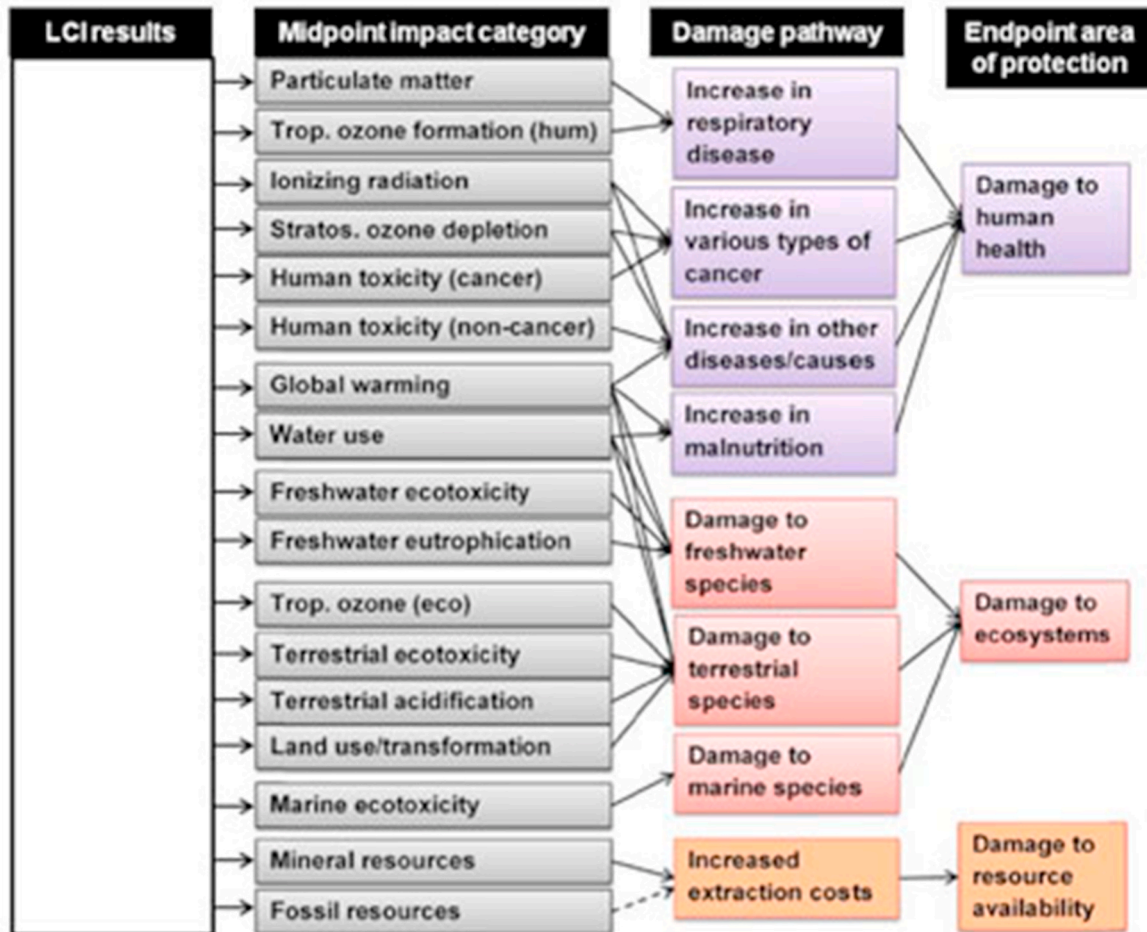


Fig. 4. Overview of the Midpoint impact categories and Endpoint Impact categories included in the Impact Assessment Method ReCiPe 2016. Source: <https://simapro.com/2017/updated-impact-assessment-methodology-recipe-2016/>.

Table 4

LCA characterized midpoint impacts associated to 1 kWh of net electricity generated in Italy according to different electricity mix assumptions.

| ReCiPe Midpoint (H) 2016 | Reference unit/kWh | Business as usual year 2021 | Scenario GOV Plan less 14% NG, year 2021-2023 | Scenario 1 Less 30% NG wind | Scenario 2 Less 30% NG solar PV | Scenario 3 Less 30% NG Nuclear | Scenario 4 Less 30% NG, en. sav. | Scenario 5 Less 30% and mix |
|---|--------------------|-----------------------------|---|-----------------------------|---------------------------------|--------------------------------|----------------------------------|-----------------------------|
| Fine particulate matter formation | kg PM2.5 eq | 7.44E-04 | 7.70E-04 | 6.77E-04 | 6.90E-04 | 6.76E-04 | 7.71E-04 | 7.01E-04 |
| Fossil resource scarcity | kg oil eq | 0.21 | 0.20 | 0.17 | 0.17 | 0.17 | 0.20 | 0.18 |
| Freshwater ecotoxicity | kg 1,4-DCB | 5.94E-03 | 6.64E-03 | 8.26E-03 | 8.00E-03 | 5.84E-03 | 6.55E-03 | 7.18E-03 |
| Freshwater eutrophication | kg P eq | 6.54E-05 | 6.98E-05 | 6.36E-05 | 6.88E-05 | 6.24E-05 | 7.10E-05 | 6.63E-05 |
| Global warming | kg CO2 eq | 0.62 | 0.60 | 0.53 | 0.54 | 0.53 | 0.61 | 0.55 |
| Human carcinogenic toxicity | kg 1,4-DCB | 6.87E-03 | 7.21E-03 | 7.47E-03 | 7.16E-03 | 6.65E-03 | 7.32E-03 | 7.14E-03 |
| Human non-carcinogenic toxicity | kg 1,4-DCB | 1.07E-01 | 1.16E-01 | 1.11E-01 | 1.32E-01 | 1.04E-01 | 1.15E-01 | 1.16E-01 |
| Ionizing radiation | kBq Co-60 eq | 0.10 | 0.10 | 0.10 | 0.10 | 0.25 | 0.11 | 0.14 |
| Land use | m2a crop eq | 8.66E-04 | 9.35E-04 | 9.51E-04 | 8.82E-04 | 8.50E-04 | 9.57E-04 | 9.08E-04 |
| Marine ecotoxicity | kg 1,4-DCB | 8.18E-03 | 9.10E-03 | 1.10E-02 | 1.08E-02 | 8.03E-03 | 8.99E-03 | 9.72E-03 |
| Marine eutrophication | kg N eq | 3.40E-04 | 3.42E-04 | 3.39E-04 | 3.45E-04 | 3.39E-04 | 3.89E-04 | 3.52E-04 |
| Mineral resource scarcity | kg Cu eq | 8.21E-04 | 8.55E-04 | 9.59E-04 | 9.44E-04 | 8.80E-04 | 8.79E-04 | 9.16E-04 |
| Ozone formation, Human health | kg NOx eq | 1.12E-03 | 1.12E-03 | 9.89E-04 | 1.00E-03 | 9.86E-04 | 1.13E-03 | 1.02E-03 |
| Ozone formation, Terrestrial ecosystems | kg NOx eq | 1.15E-03 | 1.16E-03 | 1.02E-03 | 1.03E-03 | 1.01E-03 | 1.16E-03 | 1.05E-03 |
| Stratospheric ozone depletion | kg CFC11 eq | 3.12E-07 | 3.06E-07 | 2.71E-07 | 2.74E-07 | 2.75E-07 | 3.10E-07 | 2.81E-07 |
| Terrestrial acidification | kg SO2 eq | 2.22E-03 | 2.30E-03 | 2.01E-03 | 2.05E-03 | 2.01E-03 | 2.30E-03 | 2.09E-03 |
| Terrestrial ecotoxicity | kg 1,4-DCB | 0.57 | 0.66 | 0.59 | 0.74 | 0.60 | 0.64 | 0.64 |
| Water consumption | m3 | 0.0025 | 0.0026 | 0.0024 | 0.0026 | 0.0028 | 0.0028 | 0.0027 |

Table 5

LCA endpoint impacts associated to 1 kWh of net electricity produced in Italy according to different electricity mix assumptions.

| | Business as usual year 2021 | Scenario Government Plan year 2021–2023 | Scenario 1 Less 30% NG only wind | Scenario 2 Less 30% NG only PV solar | Scenario 3 Less 30% NG only Nuclear | Scenario 4 Less 30% NG only en. eff. | Scenario 5 Less 30% and mix |
|------------|-----------------------------|---|----------------------------------|--------------------------------------|-------------------------------------|--------------------------------------|-----------------------------|
| DALY | 1.10E-06 | 1.10E-06 | 9.76E-07 | 9.94E-07 | 9.72E-07 | 1.11E-06 | 1.01E-06 |
| Species*yr | 2.45E-09 | 2.43E-09 | 2.15E-09 | 2.18E-09 | 2.14E-09 | 2.45E-09 | 2.22E-09 |
| USD2013 | 7.01E-02 | 6.68E-02 | 5.83E-02 | 5.86E-02 | 5.82E-02 | 6.69E-02 | 6.03E-02 |

Italy than in the EU scenarios in the years 2030 and 2035 while they are a bit higher in the year 2040 (0.013 kBq Co-60 eq/kWh in the year 2040 versus 0.012 kBq Co-60 eq/kWh). The impacts of the EU Scenarios (2030, 2035 and 2040) are also lower than for Italy with regard to Terrestrial acidification, Terrestrial ecotoxicity, while they are higher for Land use.

Table 7 shows the endpoint impacts per 1 kWh of net electricity generated in the 2030 Government plan scenario and in the other estimated scenarios. The EU 2035 scenario resulted to be the one with the best environmental performances as the impacts to human health (2.93E-07 DALY/kWh), to species diversity (5.23E-10 species*year/kWh) and the economy (1.04E-02 USD, 2013/kWh) are lower than for the other scenarios.

3.2. Environmental impacts of the total annual electricity generated

When shifting from FU = 1 kWh to FU = total electricity production, it should be noted that the calculated impacts depend on the assumed total net yearly production. For the sake of clarity, a scenario that assumes a yearly doubling of electricity production will likely generate higher impacts in some categories than a scenario assuming 30% electricity savings thanks to increased use efficiency, also depending on the specific mix components. This makes comparison more difficult and

requires careful evaluation.

Results of the midpoint impacts related to the total electricity of the first group of scenarios are summarised in Table 8. They point out that the production of total electricity in the BAU scenario and the Government Plan scenario generate the highest impacts to the Global Warming, compared with the other scenarios. The global warming impacts in the two scenarios are 2.00E+11 kg CO2 eq/total kWh and 1.95E+11 kg CO2 eq/total kWh respectively while in the other scenarios ranges between 1.74 E+11 kg CO2 eq/total kWh (scenario 2) and 1.71E+11 kg CO2 eq/total kWh (scenarios 3 and 4). For the environmental category “ionizing radiation” the contribution of the scenario 3 (replacement of 30% of electricity from natural gas with nuclear fuel) is the highest, with 8.15E+10 kBq Co-60 eq/total kWh, while the lowest values can be found in the scenario 4, with a value of 3.16E+10 kBq Co-60 eq/total kWh, and the scenario 1 with 3.17E+10 kBq Co-60 eq/total kWh. Further, the Scenario 3 generates the highest contribution to the water consumption category: 9.07E+08 m³/total kWh, while scenario 1 and 4 generate the lowest environmental impacts: 7.88 E+08 m³ and 7.74 E+08 m³/total kWh. All in all, the scenario 4 is the best scenario for Italy 2021–2023, as it shows the lowest impacts compared to the others, for all categories. It is also interesting to note the worsening of the environmental performances shifting from the BAU scenario to the Government Plan scenario for several impact categories except fossil resource scarcity, Global

Table 6
LCA characterized impacts associated to 1 kWh of electricity produced in the smarter research scenarios.

| ReCiPe Midpoint (H) 2016 Impact categories | Unit/kWh | Scenario GOV Plan 2030 | Scenario Italy 2030 | Scenario Italy 2035 | Scenario Italy 2040 | Scenario EU 2030 | Scenario EU 2035 | Scenario EU 2040 |
|--|--------------|------------------------|---------------------|---------------------|---------------------|------------------|------------------|------------------|
| Fine particulate matter formation | kg PM2.5 eq | 6.61E-04 | 3.83E-04 | 2.65E-04 | 3.76E-04 | 3.09E-04 | 2.13E-04 | 2.76E-04 |
| Fossil resource scarcity | kg oil eq | 0.13 | 0.07 | 0.04 | 0.07 | 0.05 | 0.03 | 0.05 |
| Freshwater ecotoxicity | kg 1,4-DCB | 1.07E-02 | 1.48E-02 | 1.69E-02 | 1.47E-02 | 1.39E-02 | 1.73E-02 | 1.44E-02 |
| Freshwater eutrophication | kg P eq | 7.41E-05 | 5.01E-05 | 3.97E-05 | 5.30E-05 | 4.39E-05 | 3.55E-05 | 4.27E-05 |
| Global warming | kg CO2 eq | 0.44 | 0.24 | 0.12 | 0.24 | 0.18 | 0.10 | 0.16 |
| Human carcinogenic toxicity | kg 1,4-DCB | 7.90E-03 | 7.38E-03 | 6.95E-03 | 7.03E-03 | 7.32E-03 | 7.31E-03 | 7.06E-03 |
| Human non-carcinogenic toxicity | kg 1,4-DCB | 1.56E-01 | 1.57E-01 | 1.73E-01 | 1.74E-01 | 1.29E-01 | 1.53E-01 | 1.32E-01 |
| Ionizing radiation | kBq Co-60 eq | 0.098 | 0.013 | 0.010 | 0.013 | 0.187 | 0.032 | 0.012 |
| Land use | m2a crop eq | 9.97E-04 | 7.84E-04 | 6.14E-04 | 7.03E-04 | 8.29E-04 | 6.93E-04 | 7.89E-04 |
| Marine ecotoxicity | kg 1,4-DCB | 1.43E-02 | 1.91E-02 | 2.17E-02 | 1.90E-02 | 1.77E-02 | 2.19E-02 | 1.83E-02 |
| Marine eutrophication | kg N eq | 3.48E-04 | 9.16E-05 | 7.32E-05 | 9.04E-05 | 1.14E-04 | 8.35E-05 | 1.04E-04 |
| Mineral resource scarcity | kg Cu eq | 1.10E-03 | 1.21E-03 | 1.35E-03 | 1.20E-03 | 1.24E-03 | 1.38E-03 | 1.15E-03 |
| Ozone formation, Human health | kg NOx eq | 9.00E-04 | 5.13E-04 | 3.25E-04 | 5.03E-04 | 4.01E-04 | 2.64E-04 | 3.59E-04 |
| Ozone formation, Terrestrial ecosystems | kg NOx eq | 9.20E-04 | 5.27E-04 | 3.33E-04 | 5.17E-04 | 4.10E-04 | 2.71E-04 | 3.67E-04 |
| Stratospheric ozone depletion | kg CFC11 eq | 2.31E-07 | 1.21E-07 | 7.29E-08 | 1.20E-07 | 9.54E-08 | 5.99E-08 | 8.10E-08 |
| Terrestrial acidification | kg SO2 eq | 1.96E-03 | 1.12E-03 | 7.65E-04 | 1.10E-03 | 8.90E-04 | 6.00E-04 | 7.95E-04 |
| Terrestrial ecotoxicity | kg 1,4-DCB | 0.92 | 0.88 | 1.04 | 0.99 | 0.68 | 0.84 | 0.67 |
| Water consumption | m3 | 0.0027 | 0.0014 | 0.0014 | 0.0015 | 0.0016 | 0.0013 | 0.0012 |

Table 7
LCA endpoint impacts associated to 1 kWh of electricity produced in the research smarter scenarios.

| | Scenario GOV Plan year 2030 | Scenario Italy 2030 | Scenario Italy 2035 | Scenario Italy 2040 | Scenario EU 2030 | Scenario EU 2035 | Scenario EU 2040 |
|------------|-----------------------------|---------------------|---------------------|---------------------|------------------|------------------|------------------|
| DALY | 8.97E-07 | 5.29E-07 | 3.48E-07 | 5.26E-07 | 4.11E-07 | 2.93E-07 | 3.92E-07 |
| Species*yr | 1.89E-09 | 1.06E-09 | 6.30E-10 | 1.06E-09 | 8.12E-10 | 5.23E-10 | 7.61E-10 |
| USD2013 | 4.45E-02 | 2.50E-02 | 1.33E-02 | 2.48E-02 | 1.65E-02 | 1.04E-02 | 1.51E-02 |

Warming, ionizing radiation. Moreover, shifting from the BAU to scenario 1 some indicators show higher values: e.g. land use showing 3.07E+08 m²a crop eq/total kWh versus 2.80E+08 m²a crop eq/total kWh (BAU scenario), freshwater ecotoxicity that in scenario 1 achieves 2.67 E+09 kg 1,4-DCB and in scenario 2 achieves the value 2.58E+09 kg 1,4-DCB/total kWh versus the BAU scenario where the value is 1.92 E+09 kg 1,4-DCB/total kWh. In particular, with regard to Global Warming, a higher percent decrease of the Global Warming impact compared to the BAU scenario (Table 5) is calculated.

The contribution of the seven scenarios to the Endpoint impact categories is shown in Table 9. The Endpoint impacts are higher in the BAU (3.54 E+05 Daly; 7.91E+02 Species*yr; 2.26E+10 USD 2013), dominated by natural gas, while decrease in the other five scenarios where 30% natural gas is replaced by other options; however, these options also generate some impacts, although smaller, which explains the lower and different values in each scenario, reaching the best performance in the scenario 4 (3.10E+05 Daly; 6.86E+02 Species*yr; 1.87E+10 USD 2013), where no additional energy sources are foreseen.

Table 10 indicates the Midpoint impacts generated by the production of total net electricity in the 2030 Government plan scenario and in the smarter seven scenarios. These scenarios are characterized for much higher shares of electricity from renewables as shown in Fig. 3 and an increase of the amount of total electricity to 2030 and 2035 as underlined in the caption of Fig. 3.

The 2030 Government Plan scenario shows that e.g., for global warming (total electricity generated assumed to be constant from Government Plan, 2021–2023) the impacts decrease from 1.95E+11 kg CO₂ eq/total kWh to 1.44E+11 kg CO₂ eq/total kWh. The impacts are also

lower than for scenarios 1, 2 and 3 with less 30% natural gas group (Table 8). The analysis of the impacts of the smarter scenarios from 2030 to 2040 highlights that they decrease from 1.04 E+11 kg CO₂ eq/total kWh (Scenario Italy 2030) to 8.61E+10 kg CO₂ eq (Scenario 2035) and increase again to 1.15 E+11 kg CO₂ eq (Scenario Italy 2040).

The same path is shown in the EU scenarios where the impacts decrease for Global Warming from the EU scenario 2030 (6.84E+11 kg CO₂ eq/total kWh) to EU scenario 2035 (6.58 E+11 kg CO₂ eq/total kWh) and increase in the EU Scenario 2040 (7.04E+11 kg CO₂ eq/total kWh).

Table 11 summarizes the Endpoint impacts generated by the total electricity in the Governmental Plan to 2030 and in the smarter scenarios. It should be noted that, as in Table 9, results are not only affected by the mix of components sources but also by the different amounts of electricity produced.

4. Discussion

4.1. Evaluation and comparison of the potential environmental impacts of the different electricity production mix scenarios

Results show that the potential environmental impacts of the production of 1 kWh of electricity (or total electricity produced annually) in Italy (e.g., for global warming category), slightly decrease from the BaU scenarios to the Government plan scenario, that considers a reduction by 14% of electricity from natural gas and its replacement with coal, oil and renewables. However, also an increase of the contribution to terrestrial acidification and terrestrial ecotoxicity can be ascertained from BaU to

Table 8

LCA characterized midpoint impacts associated to the total annual electricity produced in the different mix scenarios (total kWh).

| ReCiPe Midpoint (H) 2016 | Unit | Business as usual year 2021 | Scenario GOV Plan Less 14% NG | Scenario 1 Less 30% NG only wind | Scenario 2 Less 30% NG only PV solar | Scenario 3 Less 30% NG only Nuclear | Scenario 4 Less 30% NG only en. save | Scenario 5 Less 30% mix 4 options |
|---|--------------------------|-----------------------------|-------------------------------|----------------------------------|--------------------------------------|-------------------------------------|--------------------------------------|-----------------------------------|
| Fine particulate matter formation | kg PM 2.5 eq | 2.40E+08 | 2.49E+08 | 2.19E+08 | 2.23E+08 | 2.18E+08 | 2.16E+08 | 2.19E+08 |
| Fossil resource scarcity | kg oil eq | 6.67E+10 | 6.38E+10 | 5.59E+10 | 5.63E+10 | 5.58E+10 | 5.56E+10 | 5.59E+10 |
| Freshwater ecotoxicity | kg 1,4-DCB | 1.92E+09 | 2.14E+09 | 2.67E+09 | 2.58E+09 | 1.89E+09 | 1.84E+09 | 2.24E+09 |
| Freshwater eutrophication | kg P eq | 2.11E+07 | 2.26E+07 | 2.06E+07 | 2.22E+07 | 2.02E+07 | 1.99E+07 | 2.07E+07 |
| Global warming | kg CO2 eq | 2.00E+11 | 1.95E+11 | 1.72E+11 | 1.74E+11 | 1.71E+11 | 1.71E+11 | 1.72E+11 |
| Human carcinogenic toxicity | kg 1,4-DCB | 2.22E+09 | 2.33E+09 | 2.41E+09 | 2.31E+09 | 2.15E+09 | 2.05E+09 | 2.23E+09 |
| Human non-carcinogenic toxicity | kg 1,4-DCB | 3.44E+10 | 3.75E+10 | 3.59E+10 | 4.28E+10 | 3.35E+10 | 3.22E+10 | 3.61E+10 |
| Ionizing radiation | kBq Co-60 eq | 3.21E+10 | 3.20E+10 | 3.17E+10 | 3.20E+10 | 8.15E+10 | 3.16E+10 | 4.42E+10 |
| Land use | m ² a crop eq | 2.80E+08 | 3.02E+08 | 3.07E+08 | 2.85E+08 | 2.74E+08 | 2.68E+08 | 2.84E+08 |
| Marine ecotoxicity | kg 1,4-DCB | 2.64E+09 | 2.94E+09 | 3.54E+09 | 3.50E+09 | 2.59E+09 | 2.52E+09 | 3.04E+09 |
| Marine eutrophication | kg N eq | 1.10E+08 | 1.10E+08 | 1.10E+08 | 1.11E+08 | 1.09E+08 | 1.09E+08 | 1.10E+08 |
| Mineral resource scarcity | kg Cu eq | 2.65E+08 | 2.76E+08 | 3.10E+08 | 3.05E+08 | 2.84E+08 | 2.46E+08 | 2.86E+08 |
| Ozone formation, Human health | kg NOx eq | 3.61E+08 | 3.63E+08 | 3.20E+08 | 3.24E+08 | 3.19E+08 | 3.16E+08 | 3.20E+08 |
| Ozone formation, Terrestrial ecosystems | kg NOx eq | 3.71E+08 | 3.73E+08 | 3.28E+08 | 3.33E+08 | 3.27E+08 | 3.25E+08 | 3.28E+08 |
| Stratospheric ozone depletion | kg CFC11 eq | 1.01E+05 | 9.88E+04 | 8.74E+04 | 8.85E+04 | 8.87E+04 | 8.70E+04 | 8.79E+04 |
| Terrestrial acidification | kg SO2 eq | 7.17E+08 | 7.44E+08 | 6.50E+08 | 6.62E+08 | 6.49E+08 | 6.45E+08 | 6.52E+08 |
| Terrestrial ecotoxicity | kg 1,4-DCB | 1.85E+11 | 2.13E+11 | 1.90E+11 | 2.41E+11 | 1.94E+11 | 1.80E+11 | 2.01E+11 |
| Water consumption | m ³ | 8.19E+08 | 8.33E+08 | 7.88E+08 | 8.52E+08 | 9.07E+08 | 7.74E+08 | 8.30E+08 |

Table 9

LCA endpoint impacts associated to the total annual electricity produced in the different mix scenarios (total kWh).

| | Business as usual (year 2021) | Scenario Government Plan less 14% NG | Scenario 1 Less 30% NG only wind | Scenario 2 Less 30% NG only PV solar | Scenario 3 Less 30% NG only Nuclear | Scenario 4 Less 30% NG only en. eff. | Scenario 5 Less 30% and mix |
|------------|-------------------------------|--------------------------------------|----------------------------------|--------------------------------------|-------------------------------------|--------------------------------------|-----------------------------|
| DALY | 3.54E+05 | 3.56E+05 | 3.15E+05 | 3.21E+05 | 3.14E+05 | 3.10E+05 | 3.15E+05 |
| Species*yr | 7.91E+02 | 7.85E+02 | 6.93E+02 | 7.03E+02 | 6.91E+02 | 6.86E+02 | 6.93E+02 |
| USD2013 | 2.26E+10 | 2.16E+10 | 1.88E+10 | 1.89E+10 | 1.88E+10 | 1.87E+10 | 1.88E+10 |

Governmental scenario. This is a well-known trade-off due to the development of solar energy, where the construction and decommissioning of PV modules involves the use of smaller amounts of higher toxicity chemicals (Karkour et al., 2020; Cusenza et al., 2020). However, the research in the field is looking at promising less impacting materials and technologies (e.g. perovskite solar cells, Jung and Park, 2014, Grätzel and Milić, 2019; Cali et al., 2022 and algae solar cells, LIFE SUNALGAE, 2022 and Greenfluidics, 2022). Moreover, solar PV materials have a low turnover time and their impacts could be reduced by designing PV panels for recycling and longer durability (Cali et al., 2022).

A much stronger reduction of Global Warming can be appreciated in the other scenarios (Table 4) where less 30% of electricity is generated from natural gas and is substituted with wind, solar PV, nuclear, energy efficiency and a mix of all these sources (Figure A1, Appendix). Scenario 1 and Scenario 3 show the lowest impacts per 1 kWh to Global Warming and Terrestrial Acidification while scenario 3 evidences lower impacts in Freshwater and Terrestrial Ecotoxicity. On the other hand, Scenario 1

and Government plan scenario perform better than Scenario 3 with regard to Ionizing Radiations (0.10 kBq Co-60/kWh eq versus 0.25kBq Co-60 eq/kWh in scenario 3) and Water Consumption (0.0024 m³/kWh versus 0.0028 m³/kWh). These aspects should be taken into account in Italy where some political leaders and stakeholders in energy sector support a possible return to nuclear energy. Nuclear scenarios are unlikely to be a solution to the current and medium period natural gas emergence due to the costs and time for the construction of nuclear plants (Rothwell, 2020; Ulgiati and Ghisellini, 2013) nor to climate goals, as showed in this study, given that other scenarios where solar PV or wind replace natural gas have similar Global warming performances but perform much better in the case of ionizing radiation and water consumption categories. It is worthwhile to remember that Italy is facing the worst drought of the last 70 years (Levantesi, 2020) of which the very low levels of water in the river Po (that is the most important river in Italy) is one of the symbols. The higher temperatures are causing a process of ‘Mediterraneanization’ to the river regime of Northern Italy where rivers increasingly become intermittent, as water can disappear from the

Table 10

LCA characterized midpoint impacts associated to the total electricity production (total kWh) in the Governmental plan 2030 scenario and in the smarter scenarios.

| ReCiPe Midpoint (H) 2016 Impact categories | Unit/kWh | Scenario GOV Plan year 2030 | Scenario Italy 2030 | Scenario Italy 2035 | Scenario Italy 2040 | Scenario EU 2030 | Scenario EU 2035 | Scenario EU 2040 |
|--|--------------|-----------------------------|---------------------|---------------------|---------------------|------------------|------------------|------------------|
| Fine particulate matter formation | kg PM2.5 eq | 2.14E+08 | 1.66E+08 | 1.84E+08 | 1.80E+08 | 1.16E+09 | 1.36E+09 | 1.20E+09 |
| Fossil resource scarcity | kg oil eq | 4.36E+10 | 3.23E+10 | 2.54E+10 | 3.57E+10 | 1.96E+11 | 1.88E+11 | 2.01E+11 |
| Freshwater ecotoxicity | kg 1,4-DCB | 3.46E+09 | 6.42E+09 | 1.18E+10 | 7.01E+09 | 5.21E+10 | 1.10E+11 | 6.18E+10 |
| Freshwater eutrophication | kg P eq | 2.39E+07 | 2.16E+07 | 2.76E+07 | 2.54E+07 | 1.65E+08 | 2.26E+08 | 1.84E+08 |
| Global warming | kg CO2 eq | 1.44E+11 | 1.04E+11 | 8.61E+10 | 1.15E+11 | 6.84E+11 | 6.58E+11 | 7.04E+11 |
| Human carcinogenic toxicity | kg 1,4-DCB | 2.55E+09 | 3.19E+09 | 4.82E+09 | 3.36E+09 | 2.74E+10 | 4.65E+10 | 3.11E+10 |
| Human non-carcinogenic toxicity | kg 1,4-DCB | 5.04E+10 | 6.80E+10 | 1.20E+11 | 8.35E+10 | 4.84E+11 | 9.74E+11 | 5.76E+11 |
| Ionizing radiation | kBq Co-60 eq | 3.17E+10 | 5.48E+09 | 7.28E+09 | 6.27E+09 | 7.00E+11 | 2.04E+11 | 6.68E+11 |
| Land use | m2a crop eq | 3.22E+08 | 3.39E+08 | 4.26E+08 | 3.37E+08 | 3.11E+09 | 4.41E+09 | 3.42E+09 |
| Marine ecotoxicity | kg 1,4-DCB | 4.61E+09 | 8.26E+09 | 1.51E+10 | 9.10E+09 | 6.64E+10 | 1.39E+11 | 7.86E+10 |
| Marine eutrophication | kg N eq | 1.13E+08 | 3.96E+07 | 5.08E+07 | 4.33E+07 | 4.27E+08 | 5.31E+08 | 4.45E+08 |
| Mineral resource scarcity | kg Cu eq | 3.54E+08 | 5.23E+08 | 9.36E+08 | 5.74E+08 | 4.64E+09 | 8.80E+09 | 5.36E+09 |
| Ozone formation, Human health | kg NOx eq | 2.91E+08 | 2.22E+08 | 2.25E+08 | 2.41E+08 | 1.50E+09 | 1.68E+09 | 1.55E+09 |
| Ozone formation, Terrestrial ecosystems | kg NOx eq | 2.97E+08 | 2.28E+08 | 2.31E+08 | 2.47E+08 | 1.53E+09 | 1.72E+09 | 1.58E+09 |
| Stratospheric ozone depletion | kg CFC11 eq | 7.45E+04 | 5.24E+04 | 5.06E+04 | 5.76E+04 | 3.57E+05 | 3.81E+05 | 3.65E+05 |
| Terrestrial acidification | kg SO2 eq | 6.34E+08 | 4.86E+08 | 5.31E+08 | 5.25E+08 | 3.33E+09 | 3.82E+09 | 3.41E+09 |
| Terrestrial ecotoxicity | kg 1,4-DCB | 2.98E+11 | 3.79E+11 | 7.24E+11 | 4.74E+11 | 2.55E+12 | 5.37E+12 | 3.00E+12 |
| Water consumption | m3 | 8.69E+08 | 6.05E+08 | 9.69E+08 | 7.37E+08 | 6.02E+09 | 8.07E+09 | 6.53E+09 |

Table 11

Endpoint impacts of the total electricity produced (total kWh) in the Government plan 2030 scenario and in the smarter research scenarios.

| | Scenario Government Plan year 2030 | Scenario Reference Italy 2030 | Scenario Italy 2035 | Scenario Italy 2040 | Scenario Reference EU 2030 | Scenario EU 2035 | Scenario EU 2040 |
|------------|------------------------------------|-------------------------------|---------------------|---------------------|----------------------------|------------------|------------------|
| DALY | 2.90E+05 | 2.29E+05 | 2.42E+05 | 2.52E+05 | 1.58E+06 | 1.86E+06 | 1.66E+06 |
| Species*yr | 6.12E+02 | 4.60E+02 | 4.37E+02 | 5.05E+02 | 3.11E+03 | 3.33E+03 | 3.23E+03 |
| USD2013 | 1.44E+10 | 1.08E+10 | 9.21E+09 | 1.19E+10 | 6.28E+10 | 6.64E+10 | 6.38E+10 |

riverbed for many months (Levantesi, 2020). Therefore, in the case of nuclear, the energy-water nexus should be taken into account in future political plans.

The improvement of the impacts to Global Warming from the Government plan scenario of 2021–2023 to the 2030 scenario (Figure A2, Appendix) should provide an incentive to the Government towards accelerating the development of renewable energies and replacing natural gas, coal and oil in the shortest possible time. It is rather meaningful what the Italian 2021 Nobel Prize winner Giorgio Parisi said in a recent interview, that it is easier to win the Nobel Prize than to install solar panels, due to the resistance of uninformed people and huge bureaucracy (La Repubblica, 2022).

In the smarter research scenarios for Italy to the years 2030, 2035 and 2040 the contribution to Global Warming per 1 kWh produced is about half of that in the scenarios with less 30% of electricity from natural gas (Figure A3, Appendix). The smarter scenarios assume a high share from renewables (from 75% to 90%) as also proposed in the Italian Long-Term Strategy for the Reduction of Greenhouse Gas Emissions that has been adopted to lead the country to the so-called “climate neutrality” (Ministry of Environment, protection of Territory and the Sea, 2021) and meet the goals of the European Green Deal. A decreasing trend can be also found for Terrestrial acidification while in the case of ionizing radiation the reduction is much stronger in the smarter research scenarios, as they did not include imported nuclear electricity nor the construction of new nuclear plants in Italy and Europe. Very interesting is the comparison of the Ionizing radiation indicator in the smarter scenarios of Italy and EU, where impacts of existing nuclear plants are

included until their phasing-out. The contribution in Italy is very low compared to EU, in particular in the scenarios of the years 2030 (0.013 kBq Co-60 eq/kWh versus 0.187 kBq Co-60 eq/kWh) and 2035 (0.010 kBq Co-60 eq/kWh versus 0.032 kBq Co-60 eq/kWh) while the impacts are similar for the year 2040 (0.013 kBq Co-60 eq/kWh versus 0.012 kBq Co-60 eq/kWh), presumably due to the phasing out of some existing plants.

Considering the smarter research scenarios for Italy generates an improvement of the impacts to the Fossil Resource Scarcity category per kWh produced, while there is a worsening to the Freshwater ecotoxicity due to the higher shares of solar PV and wind. In Table 6 it is possible to see that in the 2030 scenario of the Government Plan the production of 1 kWh releases 1.07E-02 kg 1,4-DCB, a Toxicity that is lower than the impacts of scenario Italy 2030 (1.48E-02 kg 1,4-DCB/kWh), Italy 2035 (1.69E-02 kg 1,4-DCB/kWh), and Italy 2040 (1.47E-02 kg 1,4-DCB/kWh).

The results of this study per kWh produced in Italy e.g. with regard to Global Warming category, are higher in the first group of seven scenarios compared to the previous literature (Carvalho et al., 2022; Gargiulo et al., 2020) discussed in section 2, while are similar in the case of the smarter scenarios. In Carvalho et al. (2022), the two evaluated scenarios for 2030 Italy the impact to Global Warming resulted 0.31 kg CO2 eq/kWh (EU-REF scenario for Italy) and 0.20 kg CO2 eq/kWh (Italy INECP scenario 2030). In Gargiulo et al. (2020) the contribution to Climate Change category was 0.226 kg CO2 eq/kWh in the INECP 2030 scenario, lower than the 2030 base scenario (0.357 kg CO2 eq/kWh) and the 2030 EU-REF scenario for Italy (3.14 kg CO2 eq/kWh).

Table 12

Evolution of the contribution to the investigated impact categories in the 2030 Government Plan Scenario.

| ReCiPe Midpoint (H) 2016 | Unit | Scenario Government Plan year 2021–2023 | Scenario Government Plan year 2030 |
|---|--------------|---|------------------------------------|
| Fine particulate matter formation | kg PM2.5 eq | 2.48E+08 | 2.14E+08 |
| Fossil resource scarcity | kg oil eq | 6.38E+10 | 4.36E+10 |
| Freshwater ecotoxicity | kg 1,4-DCB | 2.14E+09 | 3.46E+09 |
| Freshwater eutrophication | kg P eq | 2.26E+07 | 2.39E+07 |
| Global warming | kg CO2 eq | 1.95E+11 | 1.44E+11 |
| Human carcinogenic toxicity | kg 1,4-DCB | 2.33E+09 | 2.55E+09 |
| Human non-carcinogenic toxicity | kg 1,4-DCB | 3.74E+10 | 5.04E+10 |
| Ionizing radiation | kBq Co-60 eq | 3.20E+10 | 3.17E+10 |
| Land use | m2a crop eq | 3.02E+08 | 3.22E+08 |
| Marine ecotoxicity | kg 1,4-DCB | 2.94E+09 | 4.61E+09 |
| Marine eutrophication | kg N eq | 1.10E+08 | 1.13E+08 |
| Mineral resource scarcity | kg Cu eq | 2.76E+08 | 3.54E+08 |
| Ozone formation, Human health | kg NOx eq | 3.63E+08 | 2.91E+08 |
| Ozone formation, Terrestrial ecosystems | kg NOx eq | 3.73E+08 | 2.97E+08 |
| Stratospheric ozone depletion | kg CFC11 eq | 9.87E+04 | 7.45E+04 |
| Terrestrial acidification | kg SO2 eq | 7.43E+08 | 6.34E+08 |
| Terrestrial ecotoxicity | kg 1,4-DCB | 2.12E+11 | 2.98E+11 |
| Water consumption | m3 | 8.32E+08 | 8.69E+08 |

Table 13

Generation of the Italian electricity mix from different sources (year 2020), International energy agency-IEA.

| | | |
|--|--------------|-------------|
| Oil | 3.5 | Mtoe |
| Coal | 3.6 | Mtoe |
| Nat gas | 24.2 | Mtoe |
| Biowaste | 6.4 | Mtoe |
| Geo | 5.2 | Mtoe |
| Solar/tide/wind | 3.8 | Mtoe |
| Hydro | 3.8 | Mtoe |
| TOTAL | 50.5 | Mtoe |
| Electricity output, Italy, 2020 | 23.7 | Mtoe |
| | 2.76E+11 | kWh |
| | 275.6 | TWh |
| Average efficiency (Output/Input) | 46.9% | |

Compared to the existing studies (Gargiulo et al., 2020; Carvahlo et al., 2022) we also assessed the environmental impacts per total kWh produced as well as that of the Governmental Plan scenario and their evolution to 2030. As pointed out in the previous section, the transition towards scenarios with increasing share of renewable sources for the production of total electricity such as, e.g., in the Government 2030 Plan provides the opportunity to further reduce the contribution to Global Warming in the life cycle of electricity as shown in Figure A2 (Appendix) but also to particulate matter formation with environmental and social benefits to the population in terms of lower pollution at the local level and health benefits measured by a reduction of the endpoint indicators (e.g. 2.90E+05 Daly⁸ in the Scenario Gov. Plan 2030 versus 3.56E+05 Daly in the Scenario Gov Plan, 2021–2023) (Tables 9 and 11), decreasing the external costs of total electricity generation. These are much lower for wind and solar compared to the fossils such as hard coal, lignite, natural gas and oil (Karkour et al., 2020). Further social benefits due to natural gas reduction are related to employment opportunities as calculated by Pastore et al. (2022). There are also trade-offs in the evolution from the Scenario Gov. Plan (2021–2013) to that of 2030, as

discussed previously for the results related to the production of 1 kWh. Table 12 shows the environmental benefits and costs of the shift to 2030 scenario and the consequent worsening of the contribution to some impact categories in the life cycle of electricity requiring an adequate monitoring and planning in order to mitigate the side-effects of the energy transition.

Moreover, a further replacement of natural gas and other fossil sources with renewables would promote a huge energy efficiency improvement for the whole mix. The IEA (2022) provides data and Sankey diagrams updated to the year 2020. According to these data, we can see that the total Italian production in the year 2020 was generated as shown in Table 13, by achieving an average production efficiency of about 0.47. Brown and Ulgiati (2002) calculated an average, LCA-based EROEI (Energy Return on Energy Investment, electric energy output/fossil energy input) of about 0.25 for a coal power plant, 0.30 for an oil power plant, 0.37 for a natural gas power plant, while much higher values can be calculated for wind (13.3), geothermal (4.9), hydro (31.5, gross average of alpine plant, river plant and pumping plant) and PV (5.2) processes based on the Ecoinvent 3.1 LCA Database, where the environmental energy sources are not accounted for and only the fossil input for plant manufacturing are included for EROEI calculation. The much higher EROEIs of renewables (in terms of lower fossil energy embodied per unit of electricity output) have a positive effect on the global efficiency calculation, raising the average efficiency value to the 0.47 indicated in Table 13, a bit higher than the efficiency which could be calculated for electricity mix scenarios in Tables 1 and 3, derived from less updated values from slightly less updated values of the Ecoinvent database 3.1 (Table 3).

4.2. Interpretation of the results of this study in the light of the just energy and circular economy transitions frameworks

Previous literature interpreted the results about the environmental profiles of the electricity mixes mainly in the light of decarbonization scenario plans and policies (Carvahlo et al., 2022) or country-specific electricity challenges (increasing demand, increasing population, need for changing lifestyle, etc.) and climate and natural resource constraints

⁸ <https://www.ecoem.it/servizio/gestione-fotovoltaico/>.

(Ramirez et al., 2020; Raugei et al., 2020). In that, e.g. Ramirez et al. (2020) pointed out the importance to take into account that decarbonization policies focused on climate change could have also negative side-effects in other geographical areas and for this reason they highlighted that decarbonization is only one of the aspects to consider for a transition to sustainability.

The transition to the smarter scenarios in the years 2030, 2035 and 2040 for Italy is characterized by a relevant increase of the shares of electricity from renewables (in particular solar PV and wind). These scenarios are in line with the decarbonization goals of European Union for the year 2030, named the Fit 55% package (European Parliament, 2022c) and carbon neutrality goals in the European Green Deal to be reached at 2050 (Perissi et al., 2022) and transposed in member states decarbonization plans such as the Italian long-term strategy for the reduction of the GHGs emissions adopted in the year 2021. The implementation of such scenarios will create an increasing demand for solar PV panels, wind power plants and related raw materials (Calvo and Valero, 2022), the extraction of which is likely to create further burdens in particular to the local communities living in the mining regions, exposed to increased levels of air and water pollution as well as other external negative costs (Mancini and Sala, 2018). For example, local communities living near wind farms may suffer of increased noise and loss of land (Levenda et al., 2021). In this way, the energy transition could become the source of different types of environmental and social impacts under distributional and procedural aspects, since there could be a disproportionate distribution of the costs of the energy transition and the risk of lack of engagement and participation in decision-making of local populations for the installations of new renewable infrastructures (Levenda et al., 2021). Small scale plants are much more preferable (Ottinger, 2013) and if designed and created for experimental purposes by means of reused materials offer an opportunity of raising public awareness about the importance of renewable energies in CE transition (Schoden et al., 2019). At the same time a growing quantity of solar PV panels (Malandrino et al., 2017) and wind power plants is expected to be decommissioned from the year 2028 onwards (Mendoza et al., 2022; Schoden et al., 2019). The recycling of both solar panels and wind turbines at the end-of-life still poses several challenges (Mulvaney et al., 2021). For example, wind turbines are made of steel, aluminium and copper that are likely to achieve functional recycling rates in the range 45%–60%. Other components contained in wind turbines such as electronics and electrical materials, are recycled at 50%, while other materials, such as polyvinyl chloride, fiberglass, lubricants, paints, adhesives, concrete may have much lower recycling rates or even be landfilled (Mendoza et al., 2022; Schoden et al., 2019; Alsaleh and Sattler, 2019). Solar panels are made in a large part of glass (more than 80%), but they also contain some potentially toxic materials (e.g. lead and cadmium), rare earths (e.g., tellurium and indium) and precious materials (e.g. silver and aluminium) (Malandrino et al., 2017). The recycling rates for these materials are higher for glass and aluminium, much lower for copper and tellurium as well as indium and gallium (Malandrino et al., 2017). In European Union, solar panels are considered Waste Electrical and Electronic Equipment (WEEE), within the large appliances category and regulated by the WEEE directive (2012/19/EU) and national transposing legislations (Malandrino et al., 2017; Graedel, 2011). Their end-of-life management in Italy is also performed by the consortia of producers (e.g. ECOEM, among others)

that have implemented a certified system for the collection, transport, treatment and recycling of the photovoltaic modules in compliance with the WEEE directive, technical regulations and specific economic incentives schemes of the National Energy Services Manager (GSE in Italian).⁹ The management of solar panels through such a certification scheme may provide several environmental and social benefits, due to the fact that their treatment is performed within standardized processes and adequate technologies and the recovery becomes an opportunity for social development (jobs), economic benefits (decreased demand for metals and other materials used in production) (Ghisellini et al., 2019). In this perspective, the full implementation of the concept of Circular Economy in all the stages of renewable technologies becomes crucial, in particular in their design for waste prevention (Schoden et al., 2019), disassembly, product life extension, and closed-loop recycling (Mendoza et al., 2022). To this purpose, the concept of life cycle and the use of LCA procedure are necessary (Mulvaney et al., 2021) and complementary to other assessment methods (e.g. social life cycle assessment, social impact assessment, SWOT Analysis, emergy accounting) (Bonilla-Alicea and Fu, 2022; Martinez and Komendantova, 2020; Guangul and Chala, 2019; Odum, 1996) to ensure that environmental and social hotspots and their justice implications are identified and effective solutions for improvement are considered within a systemic approach (Mulvaney et al., 2021).

4.2.1. Promoting sobriety in future energy transition

In the smarter 2030 to 2040 scenarios, it is also projected a relevant growth of electricity generated from renewables. This will have important environmental benefits in terms of reduction of GHGs emissions but other stages of the life cycle may worsen, indicating the importance of preventing the burden shift of impacts from one stage (production of electricity) to another one (e.g. extraction of the materials for solar PV). As a result, the promotion of a higher electrification that also entails a change in the habits of population (e.g. use of electricity as a fuel for cars) should occur very carefully in order to avoid the perception that electricity is 100% clean and generated without environmental costs (also think of batteries, which require materials and recycling). The limits of the natural environment in providing its functions (such as natural resources use and assimilation of waste) to the economy and society cannot be overcome and climate change is the proof of the unconstrained consumption of fossil fuels in particular in developed countries (Balzani, 2019). The ecological degradation of the Planet Earth is at an unprecedented level and is coupled to a social crisis due to the unjust distribution of resources among the worldwide population, requiring an integrated approach to fight poverty and social exclusion as well as to preserve the natural environment. Balzani (2019) underlines that the goals of social and environmental sustainability can be achieved by means of three transitions: from fossil fuels to renewables, from linear to circular economy and from consumerism to sobriety. The latter concept, in turn, acts on “things” to improve their efficiency (e.g., cars that consume less fuel and impact less) as well as on “people” to promote much virtuous behaviours, aimed to avoid the unnecessary use of energy and material resources (Balzani, 2019)¹⁰. As a result, in particular in developed countries, the energy transition towards renewable sources would lead to the implementation of “energy sobriety” with the aim of reducing energy use, inequalities among worldwide population and finally the associated environmental degradation (Hickel and

⁹ Swiss scientists have estimated that 2000 W (about 1,5 toeq/year per person) represents a sufficient amount of energy to live comfortably and the Swiss government has thus proposed a law to decrease to 2000 W the energy consumption per person (presently around 4700 W) by 2050–2100.19 Such a law, in the form of a referendum, has been approved on May 21, 2017 by Swiss citizens. Thus, for people living in rich nations reducing energy consumption is indeed possible without compromising the quality of life, which is good news.

Slamersak, 2022; Fleurbaey et al., 2014). This will not imply a reduction of the quality of life in wealthier nations since their energy use far exceeds what is required to meet human needs (Balzani, 2019), while more than 3 billion of people in poorer nations still live in energy poverty and do not have enough energy to achieve a decent quality of life (Hickel and Slamersak, 2022).

5. Conclusions and implications

This study has assessed by means of LCA the electricity generation mix of Italy under different scenarios, including the one modelled on the basis of the measures for the electricity sector adopted by the Government to face the current natural gas emergence. Two functional units have been considered in the LCA to assess both the environmental efficiency of each source per kWh of net electricity generated as well as the impacts of total electricity generated annually. Midpoint and Endpoint impact indicators have been used to measure and inform about the environmental and social benefits and costs of electricity mix generation. In Italy and other European countries, natural gas is one of the most important sources for the production of electricity. The main goal of this study has been evaluating and comparing the potential environmental impacts of the different electricity generation mix scenarios for Italy from the BAU (data of the year 2021) and Government Plan (data of the year 2021–2023) to 2030 as well as comparing them with selected EU smarter research electricity scenarios that capture the future orientation from 2030 to 2040 of the EU climate policy for the achievement of the so-called climate neutrality.

The results point out that.

- The impacts of the total electricity generated under the scenario of the Government Plan (which replaces 14% of electricity from natural gas with coal, oil and renewables) produce similar impacts to the BAU scenario in the case of Global Warming and a worsening of several impact categories such as particular matter formation, terrestrial acidification and eco-toxicity and water consumption.
- The transition towards scenarios with increasing levels of substitution of natural gas with renewable sources by 30%–60% as in the 2030 Government Plan scenario reduces the contribution to global warming and other categories while for worsening other aspects, such as terrestrial ecotoxicity, in so calling for additional technological improvements for PV and other renewables. However, the research for renewable energies (such as for solar panels and wind power) is progressing in order to find less toxic materials as well as designing them for a longer life and for an easy disassembly and recycling.
- The implementation of the concept of CE is critical and highly recommended for renewable energies plants. It is important to remind that the latter also have higher energy ratios (EROEIs) compared to electricity plants based on fossils, contributing to increase the overall efficiency of the electricity mix. This provides a further incentive for Italy and Europe to accelerate to the largest possible extent the energy transition to renewables and reduce the dependence on natural gas, while also abandoning the unsustainable idea of introducing nuclear power again, a solution unable to provide the needed fast and cheap solution to the natural gas emergence for electricity generation, not to mention the still lacking solution, locally and worldwide, for permanent disposal of nuclear waste.
- The energy transition to a higher share of renewables will provide environmental and social benefits as well as costs to be addressed

and removed, in the whole life cycle of electricity generation. The costs of the energy transition can be mitigated by the adoption of the CE principles in the design of renewable technologies. LCA is then important to evaluate the environmental soundness of circular solutions in energy transition, coupled to other approaches (e.g. social life cycle assessment). LCA is therefore fundamental in this stage toward 2030 and beyond in order to ensure that both transitions meet the three dimension of sustainability and that winners and losers in the life cycle of electricity generation and use are identified and better solutions promoted.

This paper contributes to knowledge building, by integrating the LCA evaluation of the Italian electricity mix with midpoint and endpoint indicators, two different functional units, net energy analysis, “new” concepts (just energy and CE transition). It reflects the need to develop theoretical and interpretative frameworks to advance knowledge on environmental and social impacts of the electricity mix under different political and research perspectives, in order to face the current complex environmental, energy and social challenges. With this in mind, the designed frameworks must be based on the adoption of integrated assessment methods (that also include LCA) and on the improvement of the information to be provided to all stakeholders in the energy sector.

Finally, in terms of practical implications, the electricity transition should also be combined with innovative lifestyles, in particular in wealthier nations, as suggested by the Italian Government but also in other European countries, leading to the adoption of an energy sobriety concept, driven by the awareness that even renewable electricity (as shown this study) has environmental and social costs and justice implications. Future research may certainly take advantage of expanded LCA frameworks and knowledge and further deepen the assessment of environmental impacts and costs generated by the electricity sector by means of social life cycle assessment and benefits from the identified hotspots and environmental midpoint and endpoint indicators.

Author contributions

Conceptualization: P.G., S.U.; Methodology: P.G., S.U.; Writing—original draft preparation: P.G.; Writing—review and editing: P.G., R.P., S.U.; Supervision: S.U.; Project administration: R.P.; Funding acquisition: R.P. All authors have read and agreed to the submitted revised version of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data used in this study have been collected from public statistics and private database

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APPENDIX

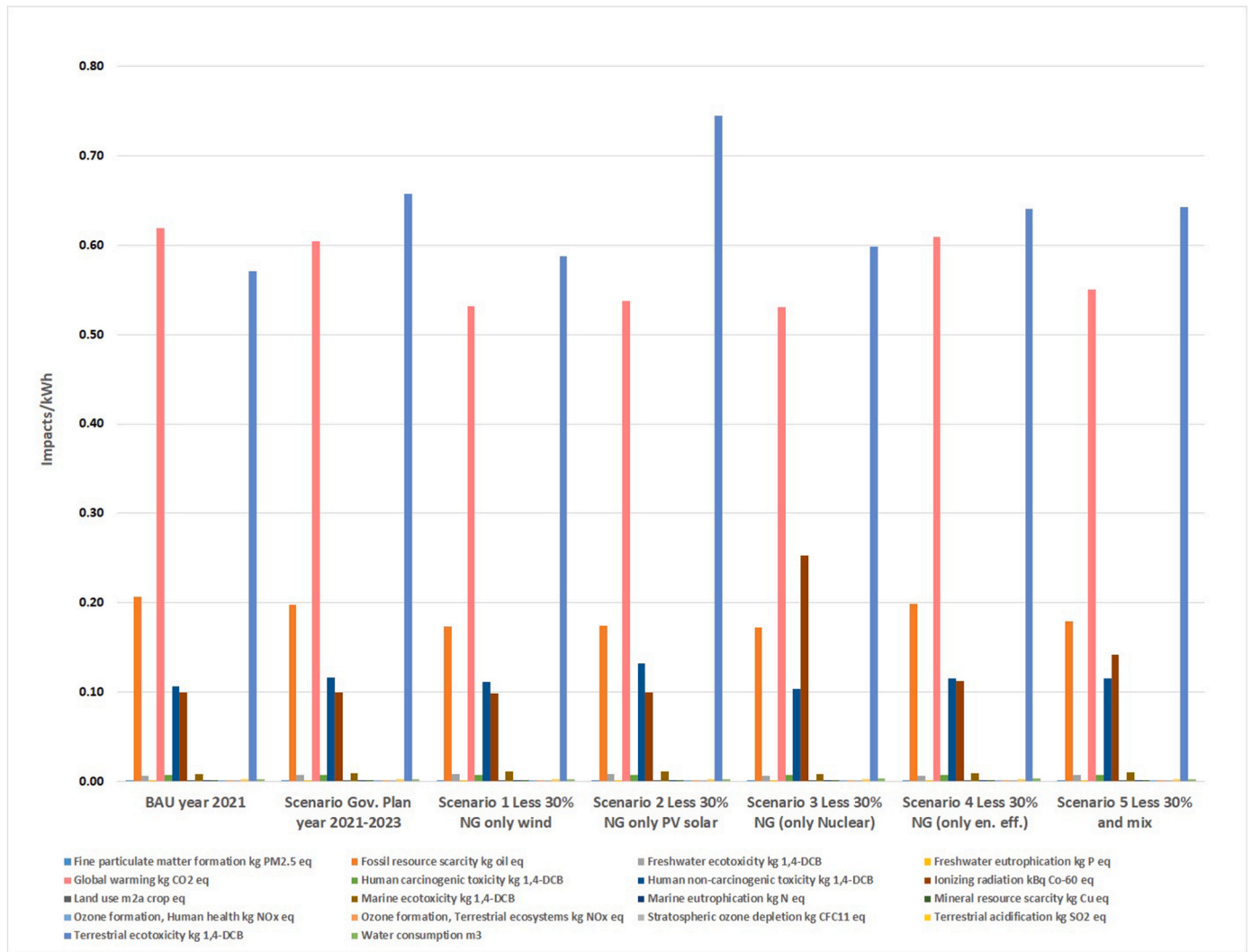


Fig. A1. LCA Environmental characterized midpoint impacts associated to 1 kWh of net electricity generated in the BAU and other scenarios with less natural gas from 14% (Government plan 2021–2023) to 30% (scenarios from 1 to 5). It should be noted that characterized impacts diagrams use different units per each impact category, which explain that some categories are represented by higher and more visible bars than others, not necessarily corresponding to higher impacts and potential damages.

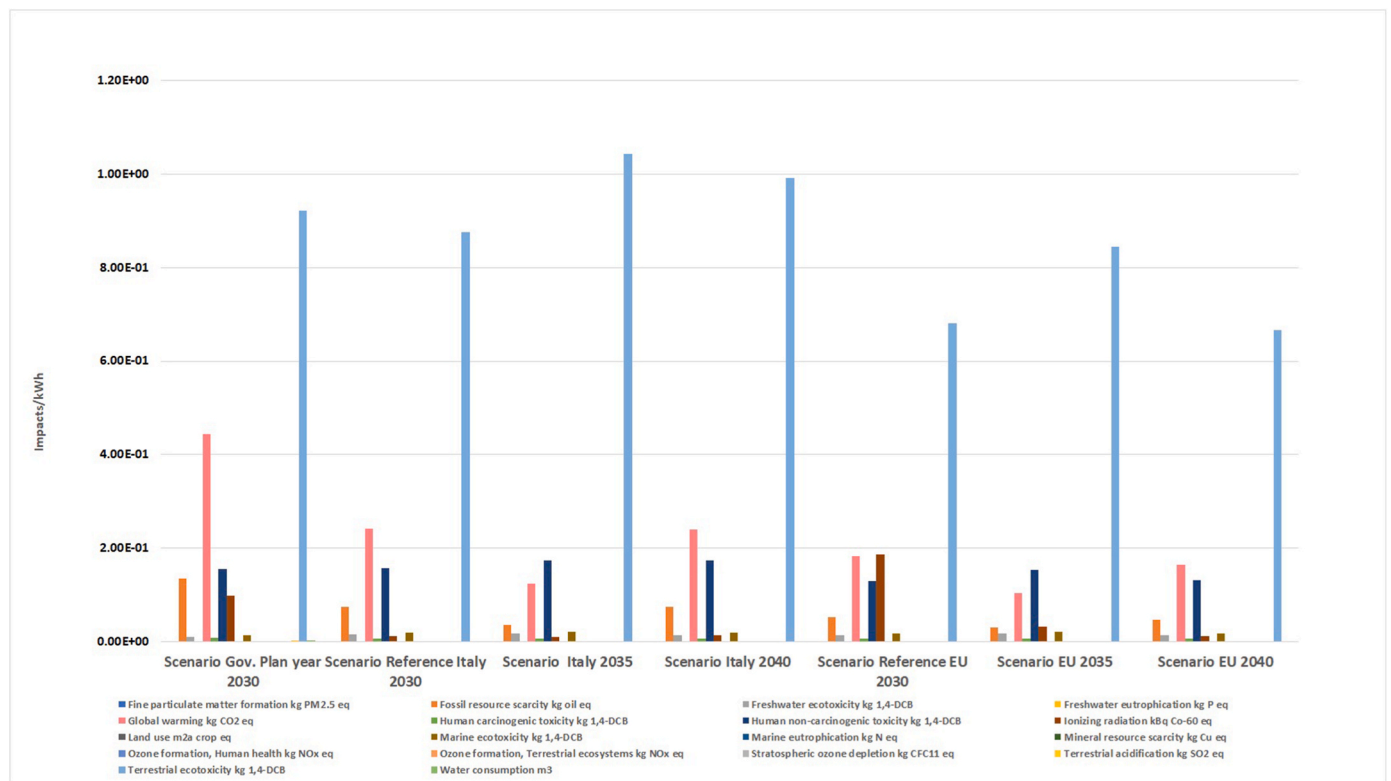


Fig. A2. LCA Environmental characterized midpoint impacts associated to 1 kWh of net electricity generated in the smarter scenarios. It should be noted that characterized impacts diagrams use different units per each impact category, which explain that some categories are represented by higher and more visible bars than others, not necessarily corresponding to higher impacts and potential damages.

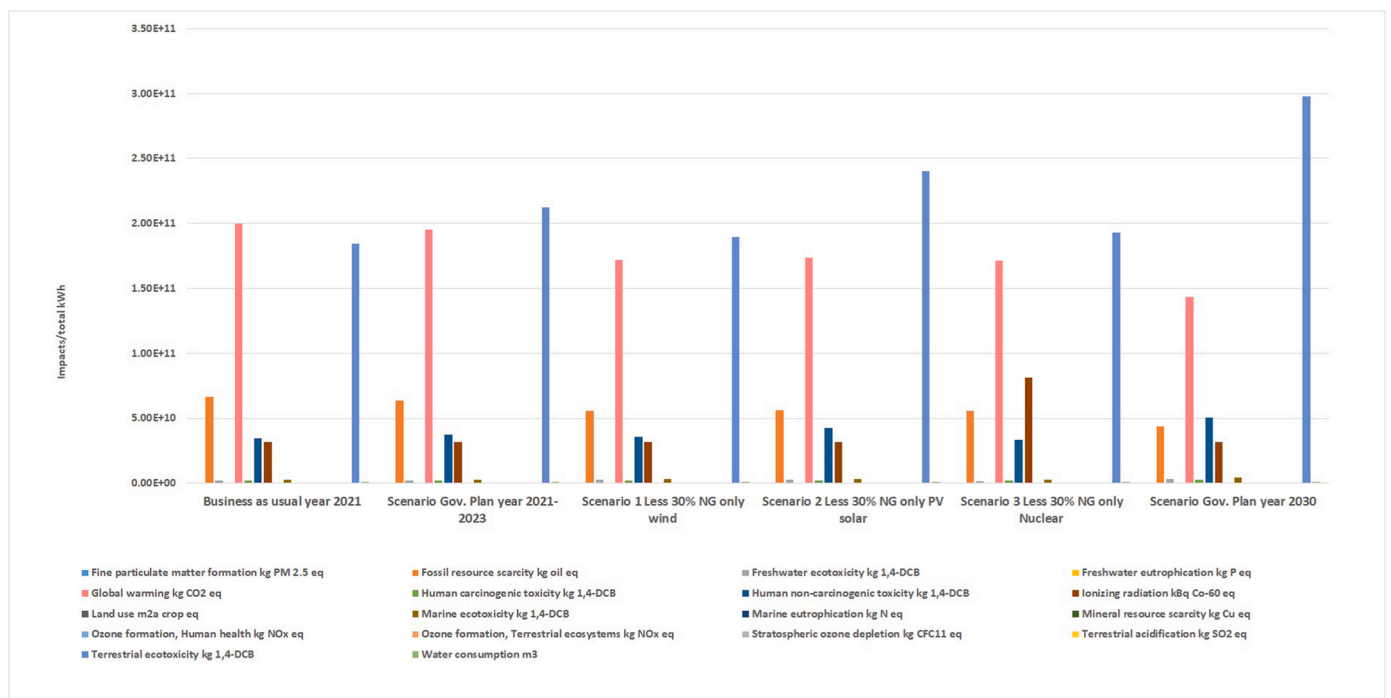


Fig. A3. LCA Environmental characterized midpoint impacts associated to net total annual electricity generated (322, 838 GWh) from the BAU (year 2021) to the 2030 Government Plan scenario (the total net electricity is assumed to be constant in these scenarios). It should be noted that characterized impacts diagrams use

different units per each impact category, which explain that some categories are represented by higher and more visible bars than others, not necessarily corresponding to higher impacts and potential damages.

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