

Life Cycle Air Emissions External Costs of the current and future Italian electricity generation

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ABSTRACT

Combining Life Cycle Assessment with monetary evaluation, the study presents an environmental estimation of externalities associated with the life cycle of electricity generation in Italy. The analysis quantifies the external costs of air emissions (greenhouse gases and air pollutants) of the current Italian electricity mix (2022) and of two future projections based on decarbonization scenarios (2030 and 2040) presenting a methodological approach based on the regionalization of life cycle air emissions.

The results show greenhouse gases contribute over 90% of total externalities, predominantly generating in Italy. National and EU policies aimed at internalizing or compensating for these externalities could be swiftly implemented and prove effective in reducing the externalities of electricity generation. Furthermore, the progressive decarbonization of electricity generation mix leads to a 67.7% reduction in externalities per kWh from 2022 to 2040. The findings also highlight that the effects of the energy transition extend along the externality chain. Externalities shift away from fossil-fuel-exporting countries toward producers of the renewable technologies required for the transition, primarily China. They also move from fuels to renewable-energy infrastructure. The detailed regionalized analysis of emissions across different life cycle phases and geographic areas offers valuable insights for policymakers aiming to internalize these externalities and support a sustainable energy transition. In this regard, the study highlights effective climate and environmental policy should combine national decarbonization of electricity generation with targeted measures to decarbonize the manufacturing supply chains of renewable-energy technologies in principal producing countries to ensure that the environmental benefits are maximized globally.

1. Introduction

The European decarbonization targets for electricity generation have driven all European countries towards production mixes with an increasing share of renewable energy sources [1]. However, a comprehensive evaluation of these policies must include not only emissions from the conversion of primary energy into electricity but also those embodied in construction, decommissioning of facilities, and the procurement of the energy source [2]. In this context, Life Cycle Assessment (LCA) is the most widely adopted tool for evaluating the environmental sustainability of a product or service [3], as it employs a holistic approach to estimate the system's environmental performance across all stages of its life cycle [4,5]. Nevertheless, the complexity of the various environmental indicators used in LCA methodologies can make it difficult for non-expert audiences to fully interpret and understand the

results; this poses challenges for decision-makers and stakeholders to guide sustainability strategies [6,7]. One potential approach to overcoming this challenge is integrating LCA methodology with monetary evaluations which enables the expression of complex results through a single economic indicator. In this regard, San Miguel (2024) pointed out that monetizing external costs provides a means to quantify the magnitude and relative significance of environmental impacts, thereby facilitating the aggregation of different indicators into a single monetary measure [8]; while Iribarren et al. (2020) stated that incorporating external costs of life cycle impacts into the decision-making process emerges as a promising strategy for effective energy planning [9].

In this context, some studies have combined both LCA and monetary evaluation methodologies to assess the environmental externalities of electricity generation. These investigations have either compared various generation technologies [10,11], analysed the electricity mixes

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of different countries [12,13], or employed different methods for estimating externalities [14]. However, most studies pointed out significant variability in results, primarily due to the wide methodological heterogeneity in estimating environmental externalities. This heterogeneity is especially pronounced in the determination of the most appropriate damage factors (also defined as cost factors or monetary valuation coefficients), namely the factors that enable the conversion of LCA results into economic terms [8,14]. To date, no standardized methodology is available that integrates LCA with monetary evaluations for the estimation of environmental externalities. In this regard, it is worth noting that most of the studies adopted damage factors which refer only to the geographical area of the use phase [15]; that is the country considered for the electricity production. Nevertheless, as discussed by Girardi et al. (2020) [15] in their study on the assessment of environmental externalities in the transport sector, the damage factors can vary significantly depending on the geographical context being determined by local physical, economic and social conditions. Therefore, conducting an external costs assessment without considering the different geographical context of the various life cycle phases (e.g., where the fossil fuels are extracted and processed or where the photovoltaic modules or wind turbines components are produced) could lead to non-negligible mistakes [15]. Thus, in response to this critical issue identified, the present study contributes by proposing a methodological approach for estimating the environmental externalities of the regionalized life-cycle air emissions associated with electricity generation in Italy considering both the current generation and future projections in line with decarbonization scenarios. The study provides an update to the methodological framework presented by Girardi et al. (2020) [15] and adapts it specifically for application to the electricity-generation sector.

Therefore, the main aim of this study is twofold. First, to present a methodological approach that integrates LCA with monetary evaluation methods for estimating the environmental externalities of electricity generation sector, focusing on regionalization of life cycle emissions. Second, to quantify the externalities of the current Italian electricity mix and to assess changes under future generation scenarios to evaluate the effectiveness of decarbonization strategies providing useful indications for strategies aimed at achieving the carbon neutral electricity generation scenarios in Italy.

2. Materials and methods

The methodological procedure used to integrate LCA and monetary valuation was the one reported in Girardi et al. (2020) that allows to assess the air emissions externalities in each life cycle phase of the

analysed system taking into account at the same time the specific geographical areas in which such pollutant emissions occur. In this way, it is possible to incorporate in the external costs assessment the intrinsic differences in the places where emissions occur: (i) physical (pollutants dispersion); (ii) societal (population density); and (iii) economical (willingness to pay to avoid environmental damages) [15].

Fig. 1 shows the steps of the methodological procedure adopted in the study.

As shown in figure, the procedure outlined involves: conducting a detailed LCA study of Italian electricity generation through accurate modelling of the national electricity mix, utilizing updated, site-specific inventory data; regionalizing both the LCA model (i.e. assigning a geographical reference to each process and sub-process involved in the LCA) and the inventory analysis results; and estimating the environmental externalities of atmospheric emissions by applying appropriate, updated and site-specific damage factors to the regionalized life cycle inventory results.

2.1. LCA approach

The current electricity generation in Italy was assessed considering the Italian electricity mix composition in 2022 (that is the most recent year for which all official statistical data were available when the study began); instead, the future electricity generation in Italy was considered through the adoption and modelling of two future scenario: mix 2030 and mix 2040 derived by the National Integrated Climate and Energy Plan [16].

As in previous studies on the LCA of electricity generation, the functional unit of the study was defined as 1 kW-hour (kWh) of electricity deriving from the country's total gross consumption (namely Gross National Consumption - GNC). This implies the consideration of the total gross national electricity generation from all sources (excepted pumped hydro generation); international electricity imports were included in the electricity supply while exports were subtracted [17,18]. Therefore, the electricity transmission and distribution network, as well as the related losses were excluded.

In this regard, Table 1 reports the composition of the three Italian electricity mixes considered: the current mix (mix 2022) and the future scenarios (mix 2030 and mix 2040).

It is worth noting two important aspects: (i) a growing increase in energy demand is expected (about 27% from 2022 to 2040); (ii) due to the growing decarbonization of electricity generation, the composition of future mixes show a significant increase in the contribution of renewable sources (especially wind and photovoltaic) to the detriment

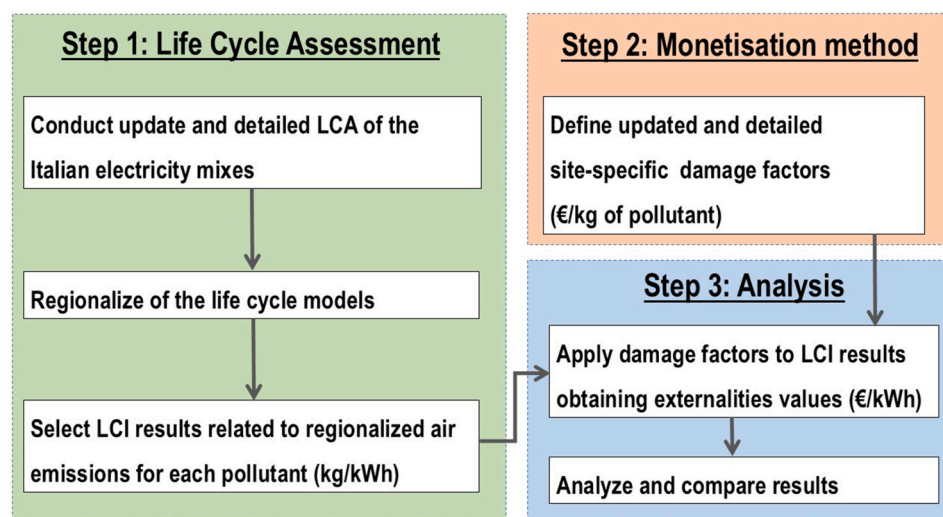


Fig. 1. Flowchart of the methodological procedure.

Table 1

Electricity generation in Italy classified by energy sources for the considered years: 2022; 2030 and 2040. Data sources [19]; for mix 2022 and [16] for mix 2030 and mix 2040.

Electricity generation source	Mix 2022		Mix 2030		Mix 2040	
	TWh	%	TWh	%	TWh	%
Biomass	17.72	5.5%	7.93	2.2%	7.79	1.9%
Geothermal	5.94	1.8%	7.23	2.0%	7.20	1.8%
Coal and derived gas ^a	24.30	7.5%	7.17	2.0%	6.24	1.5%
Natural gas	141.55	43.8%	83.36	22.7%	82.83	20.2%
Oil	15.36	4.8%	11.34	3.1%	11.93	2.9%
Hydroelectric	26.61	8.2%	46.30	12.6%	46.30	11.3%
Photovoltaic	28.23	8.7%	105.52	28.8%	158.13	38.6%
Wind	20.60	6.4%	64.13	17.5%	75.74	18.5%
Import	42.99	13.3%	33.87	9.2%	13.40	3.3%
Tot	323.30	100%	366.84	100%	409.57	100%

^a In the mix 2030 and mix 2040 this energy sources consists only of derived gases (steel gases) because it is expected that from 2030 coal will no longer be a generation source of the Italian mix.

of fossils fuels.

Future scenarios for the Italian electricity mix, indeed, indicate that photovoltaic and wind power are the most promising renewable technologies, owing to their largest technically and economically exploitable remaining potential and to declining investment costs, which make them the most competitive options for rapidly increasing renewable generation [16]. By contrast, the share of hydropower is projected to stabilize, while bioenergy is expected to decline due to limits in incentive schemes and competition with biomethane [16]. Moreover, targeted measures are planned to improve the efficiency and productivity of photovoltaic and wind technologies (e.g., high-efficiency photovoltaic systems and repowering/revamping projects for wind farms) [16].

All life cycle phases of the electricity generation were included in the system boundaries of the study: extraction and processing of fuels, transport, infrastructure components construction, power plants operation and end of life phase. As already mentioned, since the functional unit was defined in terms of GNC, the electricity transmission and distribution network, as well as the related losses were not considered.

The modelling of Italian electricity mixes was performed using SimaPro 9.5 software tool and Ecoinvent database v3.9 was the source of background inventory data.

2.1.1. Current Italian electricity mix (mix 2022)

Adopting the same modelling structure of Carvalho et al. (2022) and Gargiulo et al. (2020), the current Italian thermoelectric mix was reconstructed based on the type of plant, that means the combination of the fuel (natural gas, coal, refinery gas, diesel, biofuels, etc.) with a specific conversion technology. For thermoelectric power plants, the technologies considered are listed in the statistical reports published annually by Terna, i.e. the Italian system transmission operator [20]:

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

The fuels are all those listed in the energy balance published by Eurostat [19]. Efficiency values for each type of thermoelectric power plants were estimated dividing the energy produced by the input fuel starting from the data published by Eurostat and Terna [19,20]; while direct air emissions were derived from the environmental declarations of the EMAS-certified plants for the year 2020 [21].

Regarding to the modelling of Italian import mix of each type of fuel, the amount of natural gas, petroleum products and biofuels for each country of origin was estimated from the inventory data published by Italian Ministry of Environment and Energy Security [22] for the first two and from data included in the statistical reports published by GSE

(Gestore Servizi Energetici) Italian company [23] for the latter. A summary of data on the macro-categories of fuels are reported in Table S1 of the supplementary material.

For non-thermoelectric renewable sources, the same method is applied, associating the energy source with the conversion technology.

Photovoltaic electricity was modelled as reported in Ferrara et al. (2024), distinguishing: (i) the plant configuration type (roof-mounted or ground-mounted); (ii) the module type (polycrystalline silicon, monocrystalline silicon, amorphous silicon, CdTe, CIS); (iii) the type of monocrystalline silicon technology (Al-BSF, PERC, HJT, IBC); (iv) and plant size. In this regard, Table S2 and S3 of the supplementary material report the main inventory data as well as the values of energy yield. Further information is available in Ferrara et al. (2024).

For wind generation, only onshore wind plants were considered, distinguishing by size (plants smaller than 1 MW, plants between 1 and 3 MW, plants with a power greater than 3 MW); Table S.4 shows the distribution values and the energy yield with the data sources.

The modelling of hydropower was performed considering the distinction between: (i) reservoir plants (with a seasonal storage duration greater than 400 h); (ii) basin plants (with weekly or daily storage duration, less than 400 h and greater than 2 h); and (iv) run-of-river plants. Amount and distribution by technology are available in the statistical report of GSE [23].

For geothermal, a single technology is considered, modelled adopting a proper dataset of Ecoinvent database: "Electricity, high voltage {IT}| electricity production, deep geothermal | Cut-off, U".

2.1.2. Future scenarios of Italian electricity mix (mix 2030 and mix 2040)

The composition of the Italian mixes foreseen for 2030 and 2040 was defined based on the data provided in the National Energy and Climate Plan report [16].

The thermoelectric plants were modelled as in the mix 2022, however we modified the plant efficiencies for 2030 and 2040 according to the assumptions carried out for the development of the plan [16].

Regarding photovoltaics, the modelling used for 2022 was integrated with additional datasets related to the TOPCON (Tunnel Oxide Passivated Contact) technology, which is expected to become the leading market technology in the coming years [24]. Furthermore, the module efficiency values were adjusted to account for the impact of technological progress on the installed capacity in Italy by 2040, and the energy yield values for ground-mounted and rooftop photovoltaic plants were updated for both 2030 and 2040. Data and further information are reported in Table S2 and S3 of the supplementary material.

Similarly, the energy yield values for wind power plants were modified (see Table S4), and the offshore wind technology was added as foreseen by the NECP plan [16]. Since primary data was not available and there was no Italian offshore wind dataset in Ecoinvent database v 3.9, the modelling was based on the dataset for Denmark, adapting it to

the Italian case.

The share of electricity imports in the Italian mixes for 2030 and 2040 was considered by modelling an average European mix, which accounted for the expected electricity production in 2030 and 2040 in the EU member states. For this purpose, the data from the European Reference Scenario 2020 (EuRef2020) report was used [25].

2.1.3. Regionalization procedure of the LCA models

As reported earlier, because monetary evaluations are site-specific, estimating the external costs of life cycle emissions necessitated regionalizing the LCA modelling of the electricity mixes. This process enabled the determination of atmospheric emissions values (derived from the life cycle inventory phase) disaggregated by geographic area. Moreover, the regionalization was carried out in greater detail: after dividing emissions by geographic area, they were further classified according to life cycle stage and the energy source to which they are attributable.

As previously discussed in Girardi et al. (2020) [15], commercial LCA software and databases are not designed to handle the geographical allocation of the inventory flows. Therefore, it was necessary to investigate the geographic origin of raw materials and components imported into Italy that enter the value chain of electricity production and, accordingly, accurate geographic attribution was assigned to all relevant LCA processes. To this end, a regionalization procedure of the LCA modelling was conducted and a detailed description of this procedure as well as data sources used to regionalization are reported in the supplementary material.

In this regard, Table 2 presents the main geographic allocations of the atmospheric emissions over the life cycle of the Italian electricity mix in relation to both the life cycle stage and the generation source.

It is worth noting that some geographic allocations were performed by area rather than by individual country (e.g., “Europe” or “Rest of the World”). This approach was taken when it was not possible (or appropriate) to further disaggregate the flows of countries within the same geographic region.

2.2. Monetization methods of air emissions external costs

As mentioned at the beginning of this section, the second step of the procedure adopted for the assessment of life cycle air emissions externalities of the Italian electricity mixes considered, was to define the proper external cost factors, namely site-specific damage characterization factors expressed in €₂₀₂₂/kg of pollutant emitted (Fig. 1). This unit of measure represents the purchasing power of euro currency in year 2022 (our base year) and it remains the same for the assessment of the external costs in the 2030 and 2040 scenario, meaning that the economic assessment of future values assumes zero inflation (constant price assessment). Since the aim of the article is to assess and compare external costs related to different years in the future, a second element of the economic assessment is discounting of future damage factors to the base year 2022. Discounting methods depend on the source used for damage factors and are explained in detail in section 2.2 of the Supplementary material. The damage characterization factors discounted to the base year 2022 allow to convert the regionalized emissions values derived from each scenario's inventory results and expressed in kg of pollutant/kWh generated, into comparable monetary externality values expressed in €₂₀₂₂/kWh for each type of pollutant considered.

The literature sources selected for the monetary characterization factors are well established scientific references for external costs valuation in cost-benefit analysis: the European Commission's Handbook on the External Costs of Transport [26] and the Environmental Protection Agency (EPA) report on the Social Cost of Carbon (SCC) [27]. We included atmospheric pollutants identified by the EC Handbook [26] as primary contributors to climate change and air pollution: anthropogenic greenhouse gases (GHG - expressed in CO₂-equivalent using their Global Warming Potential) and the following air pollutants: PM_{2.5}, NO_x, SO₂,

Table 2

Allocation of electricity generation sources by geographic area and life cycle stage.

Electricity generation technology		Life Cycle Phase		
		Fuels	Infrastructure	Generation
Biomass	Liquid biofuels	Italy	-	Italy
		Germany		
		France		
		Spain		
		Hungary		
		Europe		
		Indonesia		
		Malaysia		
		Biogas	-	Italy
		Solid biofuels	-	Italy
Geothermal	Coal and derived gas	Waste	-	Italy
		-	-	Italy
		Coal	-	Italy
		Derived gas	-	Italy
		-	-	Italy
		Natural gas	-	Italy
		Italy		
		North Sea (North Europe)		
		Mediterranean Sea		
		Netherlands (only 2030 - 2040)		
Oil	Coal and derived gas	Algeria		
		Lybia		
		Russia		
		Azerbaijan ^a		
		Rest of the world		
		Italy	-	Italy
		North Sea (North Europe)		
		Mediterranean Sea		
		Netherlands		
		Algeria		
Hydroelectric	Photovoltaic	Lybia		
		Russia		
		Rest of the world		
		-	-	Italy
		-	China	Italy
		-	Europe	Italy
		-	-	Europe
		Import	-	Europe
		-	-	Europe
		-	-	Europe

^a For Azerbaijan the same damage factors of Rest of the world have been used.

NM₁₀OC, NH₃. With the exception of GHG (CO₂-eq.), we used the external cost factors recommended by the EC Handbook [26], where, for each EU member country, the cost values in euro₂₀₁₆/kg of pollutant are differentiated by emission source type, average height of release, and population exposed at the local scale. These values represent the sum of four categories of damages using the “impact pathway approach” [28]: effects on health (morbidity and mortality related to specific pollutants), agricultural production loss, damage to buildings, and biodiversity losses due to habitat damage (acidification and eutrophication).

For GHG emissions, we based the estimation of the external cost factors on the SCC estimates produced by the Environmental Protection Agency (EPA) in 2023 [27], which reflect a damage assessment approach, like the external cost factors used for air pollutants. Since the Social Cost of Carbon values recommended by EPA, measured at constant US\$₂₀₂₀, are differentiated by year of emissions for the period 2020-2080 (they increase with time in real terms) and for three near term discount rates (1.5%, 2%, 2.5%), we selected the recommended SCC values for CO₂ emissions in year 2022, 2030 and 2040 associated with the social discount rate of 2%, considered the most plausible by the EPA.

We adjusted the reference values provided by these sources (EC Handbook and EPA report) to the context of our analysis through *value transfer* techniques and then discounted future values to the base year of our assessment. The objective of value transfer techniques is to transfer

primary literature values across time and space, adapting them to each target country/year considered in the analysis and to the study's assumptions (currency, reference year). The method used in this study is the so-called unit value transfer with income adjustment, which, in addition to being relatively easy to apply, is also recommended by the EC Handbook. Value transfer techniques rely on the assumption that individuals value environmental and health goods and services (i.e. risk of death associated with an increase in air pollutant concentrations) differently according to their age, income, education, ethnic group, religion, etc. Ideally, all these differences should be taken into account when transferring a primary values (such as those estimated in the EC Handbook) to another place/point in time. However, it is very difficult to gather all the necessary information and therefore a simplified procedure called *unit value transfer with income adjustment* is often applied. The most basic version of this procedure uses income differences between the policy and the study sites to perform the conversion. A more refined version (the one applied in this work) includes an additional parameter called income elasticity of the willingness to pay for the good to be evaluated. When values must be transferred into the future, such as in this work, assumptions must be made on the income levels of the policy sites in the future and on the discount rate to be used to discount back values to the policy year (2022). More details on the value transfer technique and assumptions made are available in the supplementary materials of 2.2.

In the case of SCC we relied on the annual estimates provided by EPA (2023) for the period 2020–2080: they are global values expressed in US \$₂₀₂₀, equal for all countries. The adjustment we made is to convert EPA values in our unit of measure (euro₂₀₂₂) and then complete the discounting procedure for EPA's estimates related to CO₂ emissions in 2030 and 2040 to compare values of different years with the common economic perspective of 2022. Table 3 reports the estimated damage factors for each pollutant, calculated for the reference emission years (2022, 2030, and 2040), after discounting future-year values to the base year 2022. As a result of the value transfer and discounting procedures, we observe that the Handbook damage factors, once discounted, tend to be lower, in 2030 and 2040, with respect to values in the policy year. CO₂ damage factors decrease only slightly, since the EPA's original values gradually increase with the emission year. We underline that this apparently contradictory outcome is related only to the scope of our article, that is to compare externalities related to different time horizons with the economic meter of a common base year. According to the EPA, the externalities of future GHG emissions are estimated to increase at a compound annual growth rate of 1.25% over the 2020–2080 period. However, the valuation method we apply results in a slight reduction of characterization factors for the period 2022–2040. This outcome reflects the economic principle that damages expected to occur in future years are assigned a lower present value than immediate damages, in accordance with a social discount rate of 2%.

3. Results

The last step of the procedure shown in Fig. 1 involved the analysis and comparison of the outcomes obtained for the three Italian electricity mixes after application of the damage factors to the selected LCI results. Therefore, the following two sub-section show the obtained findings and present a comparison with other similar literature studies while the next section reports a results discussion.

3.1. Air emissions external costs of the electricity generation in Italy in 2022, 2030 and 2040

Fig. 2 shows the life cycle air emissions externalities of 1 kWh of electricity generated by the three Italian electricity mixes assessed (the current mix and the two future scenarios), while the results in numerical terms are reported in Table S5–S7 of the Supplementary material.

To provide a comprehensive overview of the study results, Fig. 2

shows the outcomes based on: (a) type of pollutant emission; (b) country where emissions occur; (c) life cycle phase and (d) type of electricity generation technology.

GHG emissions accounted for nearly all of the external costs associated with the electricity mixes, contributing between 89% and 94% depending on the mix. In contrast, the combined externalities of the other pollutant emissions were marginal, and the dominant role of GHG remained consistent regardless of the country in which the emissions occur and the type of electricity technology. Similar results were discussed also in other previous studies in which the authors highlighted the largest contribution to the external cost of electricity generation is provided by global warming, regardless of the electricity technology considered [8,12,29].

In line with decarbonization strategies for electricity generation, the comparison between the three electricity mixes highlighted the significant decrease in the overall externality, from 0.096 €/kWh for mix 2022 to 0.042 €/kWh and 0.031 €/kWh for scenarios 2030 and 2040 respectively; therefore, in agreement with Lu et al. (2021), the increasing penetration of renewables entails a significant reduction of air emissions external costs of the electricity generation [30].

Even looking at the total electricity generation in Italy for 2022, 2030 and 2040, the findings highlighted a significant decrease in the overall externalities for the future scenarios, although an increase in electricity demand of approximately 13% in 2030 and 27% in 2040 is estimated (Table 1). About this, the life cycle air emissions external costs of Italian electricity will go from approximately 30.8 billion euros in 2022 to approximately 15.5 billion and 12.6 billion euros in 2030 and 2040 respectively.

Focusing on the results in function of the geographical area in which life cycle air emissions occurred (Fig. 2 b), the central role of Italy for all considered electricity mixes emerges, while significant changes among mixes occurred in the external costs derived by the other countries. This aspect is better highlighted in Fig. 3 that shows the global spatial distribution of the life cycle air emissions external costs of the electricity generated by mix 2022 (a); mix 2030 (b) and mix 2040 (c) based on the contributions provided by the countries in which that air emissions occur, excluding the Italian contribution in order to make the differences between other countries clearer.

It is worth noting that, in the figure, the externality values that could not be assigned to a specific country during the regionalization process (labelled “Rest of the World (ROW)” in Table 2 and S5–S7) were uniformly distributed across all countries.

Comparing the results of mix 2022 and mix 2030 it is worth noting that the externalities values deriving from Russia decreased significantly. This aspect is mainly related to the substantial variation in the Italian import mix of natural gas. As discussed in depth by Ghisellini et al. (2023), indeed, the dramatic conflict between Russia and Ukraine led to a significant reduction of Russian gas contribution to Italian import mix of natural gas [31], and such contribution is expected to be almost negligible in 2030 and 2040 [32].

On the other hands, it is worth noting the increase of Chinese contribution provided to the overall external costs expected for the mix 2030 and 2040. This finding is due to the significant increase in the share of electricity from photovoltaic energy expected in the coming years (as shown in Table 1) that, consequently, will entail a considerably growth in photovoltaic modules production in China [3,33] which will then imported into Italy.

Another relevant aspect is the variation of the contribution provided by Europe to the total externality of the different mixes, that, in percentage terms, varied from 13% in mix 2022 to 5% in mix 2040. In this regard, it is worth pointing out that air emissions external costs generated by electricity import share and by wind infrastructure production were allocated to Europe (as well as a very small share of biomass and fossil fuel production processes). The findings reported in Fig. 2 (d) highlight the lowering of European contribution to the total externalities of the future mixes (2030 and 2040) was mainly due to the considerable

Table 3
Damage factors used in the study for the assessment of life cycle air emission externalities of the three Italian mixes considered.

Geographical area	Group name ^a	Type of pollutant (€ ₂₀₂₂ /kg)																	
		NOx			SO ₂			PM2.5			NMVOC			NH ₃			GHG (CO ₂ eq.)		
		2022	2030	2040	2022	2030	2040	2022	2030	2040	2022	2030	2040	2022	2030	2040	2022	2030	2040
Germany	DE_high	19.27	13.14	8.18	17.46	11.91	7.42	43.35	29.57	18.42	2.07	1.41	0.88	32.31	22.04	13.73	0.22	0.21	0.20
	DE_low	23.23	15.84	9.87	18.97	12.94	8.06	80.54	54.93	34.22	2.07	1.41	0.88	32.31	22.04	13.73	0.22	0.21	0.20
	DE_unknown	23.23	15.84	9.87	18.97	12.94	8.06	80.54	54.93	34.22	2.07	1.41	0.88	32.31	22.04	13.73	0.22	0.21	0.20
European Union	EU_unknown	12.69	10.47	8.24	12.69	10.47	8.24	45.35	37.39	29.45	1.40	1.15	0.91	20.38	16.80	13.23	0.22	0.21	0.20
	EU_high	10.50	8.65	6.82	11.09	9.14	7.20	22.59	18.63	14.67	1.40	1.15	0.91	20.38	16.80	13.23	0.22	0.21	0.20
Italy	IT_high_rural	13.22	11.96	10.53	13.07	11.83	10.41	24.48	22.16	19.50	1.28	1.16	1.02	25.06	22.68	19.96	0.22	0.21	0.20
	IT_low_urban	29.47	26.67	23.47	14.73	13.34	11.74	474.52	429.50	377.97	1.28	1.16	1.02	25.06	22.68	19.96	0.22	0.21	0.20
	IT_low_suburban	16.36	14.81	13.03	14.73	13.34	11.74	50.60	45.79	40.30	1.28	1.16	1.02	25.06	22.68	19.96	0.22	0.21	0.20
	IT_low_rural	17.52	15.86	13.95	14.73	13.34	11.74	91.66	82.96	73.01	1.28	1.16	1.02	25.06	22.68	19.96	0.22	0.21	0.20
	IT_unknown_rural	16.36	14.81	13.03	14.73	13.34	11.74	50.60	45.79	40.30	1.28	1.16	1.02	25.06	22.68	19.96	0.22	0.21	0.20
Rest of the world	RoW_unknown	7.26	5.77	4.34	7.26	5.77	4.34	25.95	20.60	15.50	0.80	0.63	0.48	11.66	9.26	6.97	0.22	0.21	0.20
Russia	RU_unknown	4.49	2.60	1.65	9.15	5.29	3.37	49.94	28.87	18.38	1.24	0.72	0.46	14.11	8.15	5.19	0.22	0.21	0.20
Lybia	LY_unknown	1.50	0.85	0.33	3.02	1.71	0.66	7.33	4.13	1.61	0.61	0.34	0.13	2.27	1.28	0.50	0.22	0.21	0.20
Algeria	DZ_unknown	3.26	2.94	2.55	9.13	8.23	7.15	23.97	21.61	18.78	0.70	0.63	0.54	10.70	9.64	8.38	0.22	0.21	0.20
Netherland	NL_unknown	16.75	11.47	7.18	23.49	16.09	10.07	86.91	59.54	37.27	3.26	2.23	1.40	34.89	23.90	14.96	0.22	0.21	0.20
North Sea	NOS_unknown	12.33	10.50	8.62	12.10	10.31	8.46	39.65	33.77	27.71	2.65	2.26	1.85	0.00	0.00	0.00	0.22	0.21	0.20
Mediterranean Sea	MED_unknown	3.46	3.05	2.61	10.60	9.36	8.00	28.36	25.03	21.40	0.58	0.51	0.43	0.00	0.00	0.00	0.22	0.21	0.20
Indonesia	ID_unknown	6.56	4.84	3.94	6.56	4.84	3.94	23.43	17.27	14.08	0.72	0.53	0.43	10.53	7.76	6.33	0.22	0.21	0.20
Malaysia	MY_unknown	10.22	8.52	5.86	10.22	8.52	5.86	36.50	30.43	20.92	1.12	0.94	0.64	16.40	13.68	9.40	0.22	0.21	0.20
France	FR_unknown	19.93	16.00	12.15	16.02	12.85	9.76	47.25	37.92	28.81	1.73	1.39	1.05	17.74	14.24	10.82	0.22	0.21	0.20
Hungary	HU_unknown_rural	18.26	8.72	3.48	11.82	5.64	2.25	38.90	18.56	7.41	0.96	0.46	0.18	22.56	10.77	4.30	0.22	0.21	0.20
Spain	ES_unknown	5.64	4.75	3.83	7.83	6.60	5.31	22.90	19.30	15.55	0.81	0.68	0.55	7.37	6.21	5.00	0.22	0.21	0.20
China	CN_unknown	8.19	5.00	1.98	8.19	5.00	1.98	29.24	17.86	7.08	0.90	0.55	0.22	13.14	8.02	3.18	0.22	0.21	0.20
	CN_high	6.77	4.13	1.64	7.15	4.37	1.73	14.57	8.90	3.53	0.90	0.55	0.22	13.14	8.02	3.18	0.22	0.21	0.20
Global	GLO_unknown	12.89	13.49	10.28	8.03	8.40	6.40	28.68	30.02	22.87	0.88	0.93	0.70	12.89	13.49	10.28	0.22	0.21	0.20

^a Damage factors differ for: geographical area (country code); height of release for pollutant (high; low and unknown); and population density (urban, suburban and rural areas; if the indication in the group name is missing, it means “undefined”).

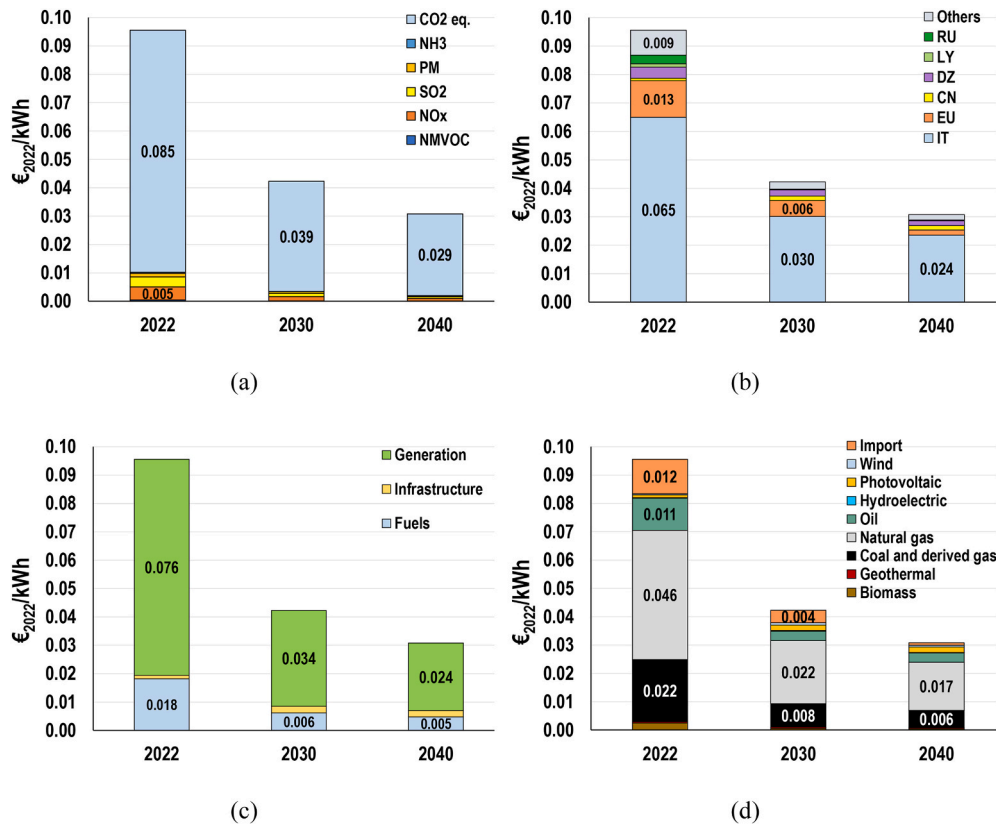


Fig. 2. Life Cycle air emissions external costs of 1 kWh of electricity produced with the current Italian mix (2022) and the two future scenarios considered (2030 and 2040) in function of: type of pollutant emission (a); country where emissions occur (b); life cycle phase (c) and type of electricity generation technology (d). Acronyms: IT: Italy; EU: Europe; CN: China; DZ: Algeria; LY: Libya; RU: Russia; Others: all the other countries.

reduction in the electricity import share expected in the composition of those mixes (see Table 1). External costs due to wind power, on the other hand, show a growth between the mix 2022 and the mix 2030, however this increase is significantly lower than the decrease in externalities due to electricity import share.

The growth of renewables expected in the composition of future mixes (above all wind and photovoltaic) is also pointed out by the obtained results in function of the life cycle phases of Italian electricity generation (Fig. 2 (c)). In fact, the increase of the external costs due to the infrastructure components production of the future mixes compared to those of the current mix was caused by the growth in the share of wind and photovoltaic electricity generation expected for 2030 and 2040.

Given the central role of greenhouse gases in determining the aggregate results, we performed a sensitivity analysis focused on variations of the key parameter corresponding to the damage factor used to monetize the externalities associated with GHG emissions. The values of this factor adopted in the study for 2022, 2030 and 2040 (Table 3) are based on the SCC values recommended by the U.S. Environmental Protection Agency (EPA) which represent the average results obtained from three alternative models to estimating climate damages [27]. Table S8 of the supplementary material reports a description of these three models and their differences as well as the damage factor values obtainable adopting each model. Therefore, these values deriving by each model (Table S8) were used as variation parameter in the sensitivity analysis and the obtained results of the aggregate air emissions externalities of the electricity mixes are reported in Table 4.

The sensitivity analysis shows that the overall variability of the results obtained with the adoption of the three EPA models is limited but non-uniform. Notably, the largest divergences occur for future projections, which are intrinsically subject to greater uncertainty.

3.2. Air emissions externalities of electricity generation technologies in Italy

Leaving the perspective of the electricity generated by Italian mixes with a specific composition referred to a reference year (in this study 2022, 2030 e 2040); it is interesting to assess the life cycle air emissions external costs of electricity production from different technologies in Italy. In this regard, Fig. 4 shows the externalities of 1 kWh of electricity generated with the different types of technologies in Italy in 2022 making explicit the contributions provided by the countries where emissions occur (a) and the phases of electricity generation life cycle (b).

In accordance with previous studies, fossil fuels-based technologies showed external costs higher an order of magnitude than the other type of technologies [11,13]; with the coal-based technologies that reached the highest value [34,35].

As already pointed out by other authors, this is mainly due to the air emissions occur during the combustion process of the fossil fuels [36]; indeed, as shown in Fig. 4 about 80% of the total life cycle air emission externalities of these technologies happen in Italy (a) during the electricity generation phase (b). For each type of fossil fuels-based technology considered, the remaining 20% of total externalities was due to the fuel production phase, composed by the extraction, processing and transport of fuel. In this regard, Fig. 4 (a) shows the contribution provided by each country from which Italy imported natural gas, coal and oil in 2022 and to which the air emissions generated in the fuel production phase were allocated.

Looking at the externalities in function of the type of pollutant emission (reported in Table S9 of the supplementary material), for each power generation technologies the same trend of results already obtained for the Italian mixes is observed: the GHG emissions play a central role for each energy source, with a contribution provided to the total

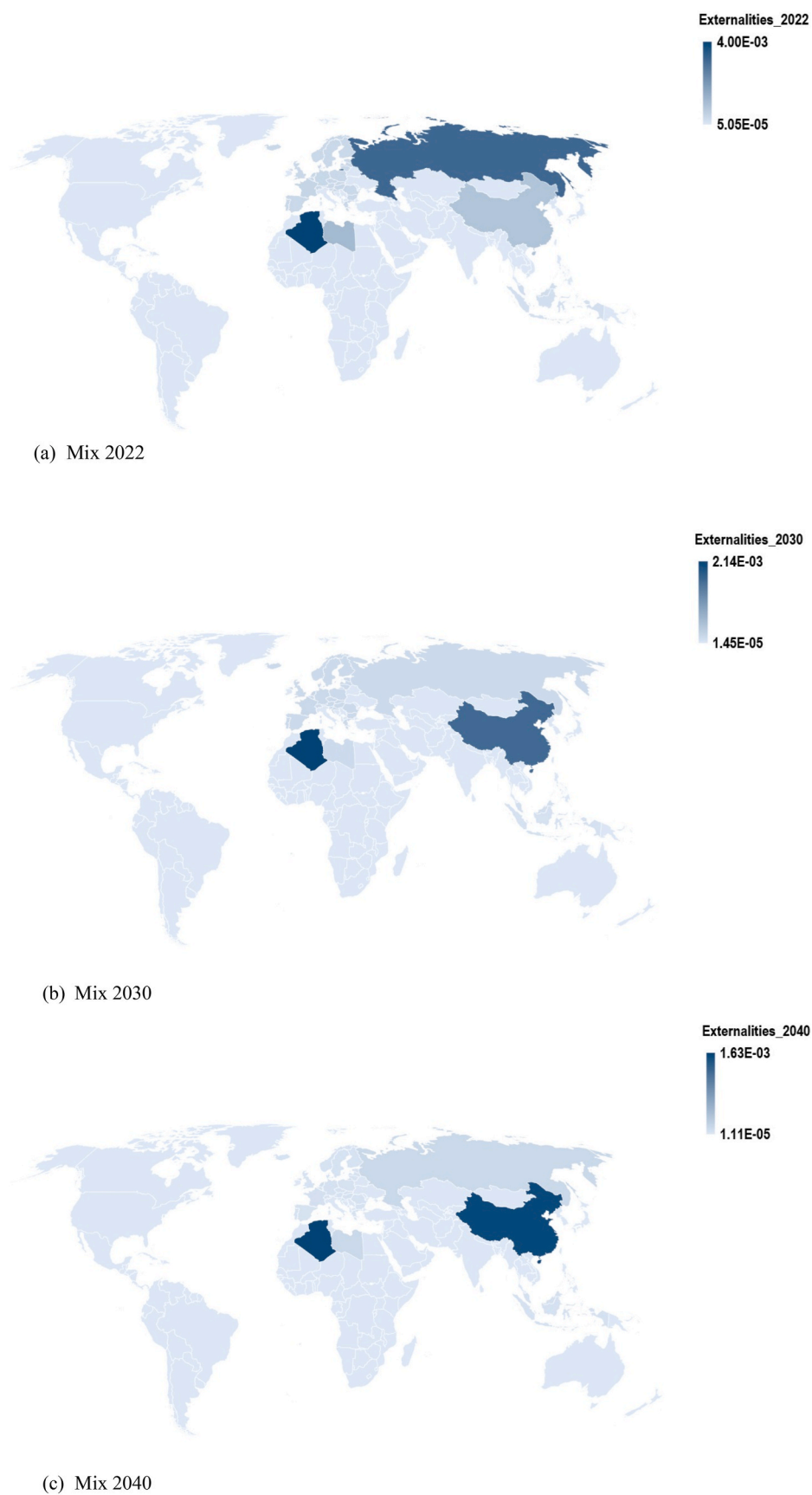
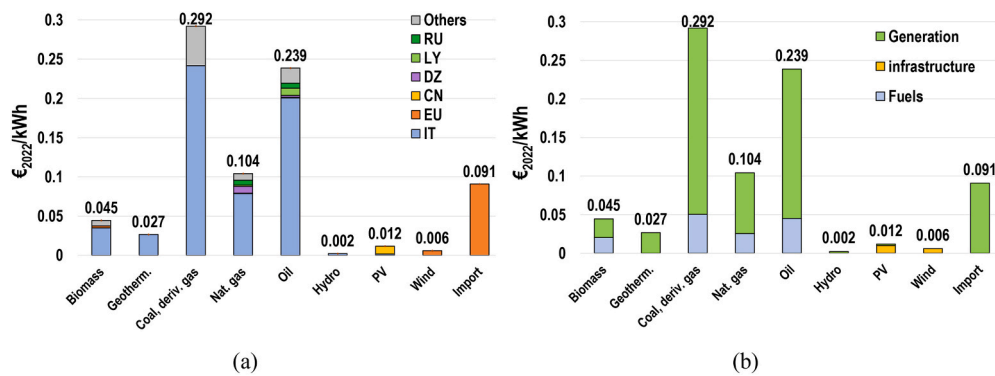


Fig. 3. Spatial distribution of the overall externality of the Italian electricity mixes: 2022 (a); 2030 (b) and 2040 (c) based on the contributions provided by the different countries where the life cycle air emissions occur (excluding the Italian contribution).

Table 4

Sensitivity analysis results on the variation of the EPA models used for the estimation of the damage factor associated with the GHG emissions.

EPA Models	2022		2030		2040	
	(€/kWh)	Variation (%)	(€/kWh)	Variation (%)	(€/kWh)	Variation (%)
DSCIM	0.0949	−0.7%	0.0423	0.2%	0.0321	4.4%
GIVE	0.0937	−1.9%	0.0407	−3.7%	0.0290	−5.8%
Meta-analysis	0.0988	3.4%	0.0440	4.1%	0.0311	1.1%
EPA (average EPA values used in this study)	0.0955	-	0.0422	-	0.0308	-

**Fig. 4.** Life cycle air emissions external costs of 1 kWh of electricity generated by the different technologies. Acronyms: IT: Italy; EU: Europe; CN: China; DZ: Algeria; LY: Libya; RU: Russia; Others: all the other countries.

external costs $\geq 90\%$ for fossil fuels-based technologies and $\geq 60\%$ for renewables (except for biomass-based technologies with a CO₂ eq. contribution of about 44%).

As already mentioned, the estimation of environmental externalities from electricity generation exhibits considerable variability, as reflected in our quantitative comparison with findings from other studies [8,12]. In this regards Fig. 5 shows the distribution range of the literature results about the external costs of eight power generation technologies: three fossil fuel-based (a) and five renewables (b). For each technology, all values considered derive from studies published in the last 10 years about the environmental external costs of electricity generation in European countries.

This results variability depends on the fact that, as discussed previously, there are many different methods to estimate the external costs, that differ primarily for the choice of the environmental damages to assess in relation of a specific emission type (extension of the scope of analysis) and for methods to estimate the economic value of damages per unit of emissions [26]. However, the environmental externalities of electricity generation, as already shown, are driven by the external costs

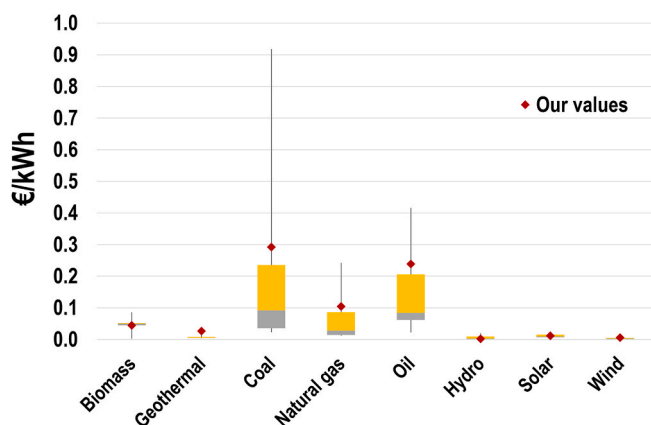
due to the GHG emissions, and this was pointed out both by the authors who assessed only the air emissions externalities of the power generation (as in this study) and by those who evaluated the external costs associated also with other environmental factors (as resources consumption). Accordingly, the findings shown in Fig. 5 highlighted renewables proved lower variability of results than fossil fuels-based technologies, and among the latter, highest variability in results was found in technologies based on a higher carbon content of the fuel (as coal and oil).

4. Discussion

Comparing the three mixes shows a substantial fall in aggregate externalities in the decarbonized scenarios. This reduction is tightly linked to the projected change in the composition of electricity mixes; principally the large increase in renewable penetration (notably solar PV and wind) and the corresponding decline in fossil-fuel generation. Therefore, moving the physical carbon-intensive processes out of the electricity generation stage (i.e., displacing gas and coal with renewables) is the principal lever for lowering total external costs [12,30].

However, it is worth noting that even with strong deployment of renewables the fossil-fuel contribution remains significant: fossil fuels account for more than 70% of total externalities even in the 2030 and 2040 mixes. This implies that residual fossil generation, imports, and upstream processes (extraction, processing, transport) continue to generate significant impacts.

The regionalization approach adopted in the study allowed to highlight that the net effect of decarbonization is a large reduction in total externalities, but with a non-negligible spatial reallocation of where remaining externalities occur: from fossil-fuel producing regions toward countries producing components for renewable technologies. Deployment of low-carbon technologies in the consuming country can transfer a portion of external burdens to countries that host manufacturing. Therefore, to fully realize the global environmental benefits of renewable deployment, efforts are necessary to decarbonize photovoltaic and wind-turbine manufacturing considering that, for example, energy demands in PV's components manufacturing are primarily supplied from fossil fuels [39]. Even policies focused on

**Fig. 5.** Environmental external costs of European power generation technologies assessed by studies published in the last ten years [8,13,14,29,30,37,38].

circularity can provide a very significant contribution: increasing components lifetime, improving recycling rates, and requiring responsible end-of-life handling can reduce environmental burdens per unit of delivered electricity and diminish externality transfers [3].

From a methodological perspective, the comparison with the literature results underlined a significant variability in estimated air emissions externalities associated with electricity generation. As noted in the previous section, this variability is due to differences in monetization methods adopted; particularly those used to assess the GHG emissions (expressed as CO₂ eq.). In fact, the choice of the economic method for the estimation of the GHG cost factors takes on crucial importance [8] and is also the main reason why the external costs of the power generation technologies obtained in this study are generally higher than the third quartile of the literature results (as shown in Fig. 5). In the literature, two main approaches have emerged for evaluating the external costs of greenhouse gases: the method of the present value of the expected damages associated with additional emissions (also known as the Social Cost of Carbon, SCC and the method of emission reduction costs to a predetermined policy target (known as the Avoidance Cost or more precisely Abatement cost method). The choice between the two methods is not neutral: economic theory posits that the SCC only represents the externalities related to climate risk, while the Abatement cost method is theoretically a second best option: the SCC value is higher than the early costs of emission reductions, while these costs tend to increase in the long term (due to the gradual exhaustion of the emission reduction potential associated with less costly solutions), eventually reaching the level of the marginal benefits of reduction (the SCC) [40,41]. Studies considered in the comparison represented in Fig. 5 are often based on the value of 100 USD/t CO₂ recommended by the EC Handbook [26], obtained with the Abatement cost approach to a target level of 2 °C of climate warming. Alternatively, they use the observed price of emission permits under the EU-ETS (which can be seen as a particular case of the abatement cost approach, applying a short-term European rather than a long-term global policy target for emission reduction), outdated values of the SCC, or an average of different estimates obtained with the two approaches. The same Handbook acknowledges that the EU-ETS price does not reflect the social costs of CO₂ emissions and that the abatement cost approach to a 2 °C climate target, when used to estimate the externalities of emissions, is only a second-best choice dictated by pragmatic reasons. It is adopted because estimates obtained with the economic theory's preferred method are too uncertain and provide very low values (lower than the EC-recommended 100 USD/t CO₂).

Unfortunately, the knowledge base of the community Handbook requires a significant update regarding the valuation of the social cost of carbon and the external costs of greenhouse gas emissions [42]. Differently to previous studies on the topic, in this article we had the opportunity to apply the SCC values recently updated by the U.S. Environmental Protection Agency (EPA) [27], which revised upwards the central estimate of the SCC (193 USD₂₀₂₀/tCO₂ 2020), nearly doubling the value recommended by the EC Handbook [26]. The publication of the EPA's report [27] on the social cost of greenhouse gas emissions at the end of 2023 marks a significant milestone in the research on the environmental damages of climate change. The EPA report comes after authoritative reports on the SCC released by the US Intergovernmental Working Group [43] and stands out as the most up-to-date and robust among those available in both academic and institutional literature [42]. The EPA's report has incorporated the recommendations made in 2018 by the NASEM [44] to improve the scientific foundations of the SCC. EPA adopted a modular approach to estimating the SCC, fundamentally based on four modules: climate science, socio-economic and emissions scenarios, damage module, and the discounting procedure for the flow of expected damages to the year of emissions. The damage module is designed to average the results of three different approaches to climate damages. Each phase of the estimation process draws on updated knowledge from relevant scientific disciplines, assembled into a single integrated assessment model

developed by the EPA itself, with its code transparently published as open source on the Agency's website [45]. When comparing the “central estimates” of the EPA report with the previous non-updated SCC value of the last IWG report (2021) [46], the difference is significant: the EPA estimate increases the SCC by +278% (from 51 USD₂₀₂₀/tCO₂ at a 3.0% rate in IWG, to 193 USD₂₀₂₀/tCO₂ at a 2.0% rate in EPA).

Recent literature reviews on the SCC highlight a clear upward trend in SCC estimates, primarily attributable to improvements in modelling, data sources, and scientific knowledge [46–48]. The EPA's estimate also indicates significant potential for further improvement, particularly in the assessment of more catastrophic and long-term phenomena [42]. It is anticipated that the upward trend in SCC estimates will persist in the future, thereby increasing the variability of results in studies on the life cycle external costs of technologies with high CO₂ eq. emissions.

5. Conclusions

The environmental externalities assessment of the life cycle air emission associated with Italian electricity generation has revealed the predominant role of greenhouse gases in the external costs of the Italian kWh, with these emissions being generated primarily within Italy. Consequently, national and EU policies aimed at internalizing or compensating for these externalities could be swiftly implemented and prove effective in reducing the external costs of electricity generation. On the other hand, the observed reduction in externalities of the electricity generation over time (0.096 €/kWh for the 2022 mix, and 0.042 €/kWh and 0.031 €/kWh for 2030 and 2040, respectively) indicates that part of this phenomenon is already underway. Moreover, the effects of the energy transition extend along the externality chain, shifting externalities from fossil fuel-exporting countries to the producers of the renewable technologies required for the transition (primarily China), and from fuels to infrastructure (specifically photovoltaic and wind installations). By facilitating international comparisons and benchmarking, the study adds to the international discourse on decarbonization and on the systematic inclusion of environmental externalities in economic decision-making frameworks, with the broader objective of fostering a more just and environmentally sustainable energy transition. In this context, our findings provide an analytical basis for the design of policy packages that go beyond uniform, technology-neutral measures and instead seek to internalize external costs with greater precision. By accounting for the heterogeneous environmental impacts of different technologies, such an approach can support the implementation of differentiated emission permit prices or the deployment of carefully targeted subsidies, thereby improving both the efficiency and the equity of climate and energy policies.

Furthermore, the results underlined the importance of a regionalized approach in analysing life-cycle emissions and in defining damage factors: such regionalization not only enables more accurate and robust monetary assessments, but also produces more detailed and meaningful results that provide information on the quantification of geographical displacement in environmental externalities by varying the composition of the electricity mix. In this regard, this study offers important suggestions for policymakers: achieving deep decarbonization in the electricity sector cannot be pursued in isolation from the upstream production processed that supply renewable energy technologies. To ensure that the transition to low-carbon power generation delivers its full environmental benefits, it is essential to implement policies that also lower the carbon intensity of the manufacturing value chains producing renewable energy equipment. Without such coordinated interventions, reductions in emissions achieved within national electricity systems may be undermined by the carbon embodied in imported turbines, panels, and other key components. This concern is particularly relevant in the current global context, where leading manufacturers of renewable energy infrastructure – above all China – continue to depend largely on fossil-fuel-dominated energy systems. Consequently, part of the environmental burden associated with renewable electricity deployment

risks being displaced to other regions rather than eliminated, limiting the overall effectiveness of national and regional decarbonization efforts.

From a methodological point of view, the wide variability observed in the assessment of the environmental externalities associated with electricity generation is mainly explained by different methods and reference values on key parameters (for instance, air pollution health costs are linked to the value of a statistical life or the value of one year of life expectancy in a specific country); therefore, it is advisable that LCA studies on externalities transparently adopt the most reliable conventions available and critically challenge these conventions when they are outdated by proposing new alternatives.

CRediT authorship contribution statement

Carmen Ferrara: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Benedetta Marmioli:** Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Andrea Molocchi:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Conceptualization. **Giulio Mela:** Writing – review & editing, Validation. **Maria Leonor Carvalho:** Validation, Supervision, Formal analysis, Conceptualization. **Pierpaolo Girardi:** Validation, Supervision, Methodology, Formal analysis, Conceptualization.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.renene.2026.125416>.

References

- [1] European Commission, National renewable energy action plans. https://energy.ec.europa.eu/index_en, 2020. (Accessed 28 March 2025).
- [2] A. Rentizelas, D. Georgakellos, Incorporating life cycle external cost in optimization of the electricity generation mix, *Energy Policy* 65 (2014) 134–149, <https://doi.org/10.1016/j.enpol.2013.10.023>.
- [3] C. Ferrara, B. Marmioli, M.L. Carvalho, P. Girardi, Life Cycle Assessment of Photovoltaic electricity production in Italy: current scenario and future developments, *Sci. Total Environ.* 948 (2024) 174846, <https://doi.org/10.1016/j.scitotenv.2024.174846>.
- [4] ISO 14040, ISO 14040:2006, ISO. <https://www.iso.org/standard/37456.html>, 2006. (Accessed 13 March 2024).
- [5] ISO 14044, ISO 14044:2006, ISO. <https://www.iso.org/standard/38498.html>, 2006. (Accessed 13 March 2024).
- [6] M.A. Curran, Strengths and limitations of life cycle assessment, in: W. Klöpffer (Ed.), *Backgr. Future Prospects Life Cycle Assess.*, Springer Netherlands, Dordrecht, 2014, pp. 189–206, https://doi.org/10.1007/978-94-017-8697-3_6.
- [7] R. Woods-Robinson, M. Carbajales-Dale, A. Cheng, G. Cooney, A. Kirchofer, H.P. H. Liddell, L. Peterson, I.D. Posen, S. Moni, S. Sleep, L. Wachs, S. Zargar, J. Bergerson, Controversy and consensus: common ground and best practices for life cycle assessment of emerging technologies. <https://doi.org/10.48550/arXiv.25.01.10382>, 2025.
- [8] G. San Miguel, External environmental costs of electricity generation using a life cycle approach: a case study of Spain, *Renew. Energy* 237 (2024) 121849, <https://doi.org/10.1016/j.renene.2024.121849>.
- [9] D. Iribarren, M. Martín-Gamboa, Z. Navas-Angueta, D. García-Gusano, J. Dufour, Influence of climate change externalities on the sustainability-oriented prioritisation of prospective energy scenarios, *Energy* 196 (2020) 117179, <https://doi.org/10.1016/j.energy.2020.117179>.
- [10] B. Huang, Y. Wang, Y. Huang, X. Xu, X. Chen, L. Duan, G. Yu, Z. Li, H. Liu, H. W. Kua, B. Xue, Life cycle cost analysis of solar energy via environmental externality monetization, *Sci. Total Environ.* 856 (2023) 158910, <https://doi.org/10.1016/j.scitotenv.2022.158910>.
- [11] C. Wang, L. Zhang, P. Zhou, Y. Chang, D. Zhou, M. Pang, H. Yin, Assessing the environmental externalities for biomass- and coal-fired electricity generation in China: a supply chain perspective, *J. Environ. Manag.* 246 (2019) 758–767, <https://doi.org/10.1016/j.jenvman.2019.06.047>.
- [12] F. Baumgärtner, P. Letmathe, External costs of electricity generation in 27 European countries from 2010–2030: pathway toward sustainability or business as usual? *PLoS One* 19 (2024) e0294499 <https://doi.org/10.1371/journal.pone.0294499>.
- [13] D. García-Gusano, I.R. Istrate, D. Iribarren, Life-cycle consequences of internalising socio-environmental externalities of power generation, *Sci. Total Environ.* 612 (2018) 386–391, <https://doi.org/10.1016/j.scitotenv.2017.08.231>.
- [14] T.L.T. Nguyen, B. Laratte, B. Guillaume, A. Hua, Quantifying environmental externalities with a view to internalizing them in the price of products, using different monetization models, *Resour. Conserv. Recycl.* 109 (2016) 13–23, <https://doi.org/10.1016/j.resconrec.2016.01.018>.
- [15] P. Girardi, C. Brambilla, G. Mela, Life cycle air emissions external costs assessment for comparing electric and traditional passenger cars, *Integrated Environ. Assess. Manag.* 16 (2020) 140–150, <https://doi.org/10.1002/ieam.4211>.
- [16] NECP, National energy and climate plans. https://commission.europa.eu/energy-climate-change-environment/implementation-eu-countries/energy-and-climate-governance-and-reporting/national-energy-and-climate-plans_en, 2023. (Accessed 3 April 2024).
- [17] M.L. Carvalho, B. Marmioli, P. Girardi, Life cycle assessment of Italian electricity production and comparison with the European context, *Energy Rep.* 8 (2022) 561–568, <https://doi.org/10.1016/j.egyr.2022.02.252>.
- [18] A. Gargiulo, M.L. Carvalho, P. Girardi, Life cycle assessment of Italian electricity scenarios to 2030, *Energies* 13 (2020) 3852, <https://doi.org/10.3390/en13153852>.
- [19] Eurostat, Energy Balance | statistics. https://ec.europa.eu/eurostat/databrowser/view/nrg_bal_c/default/table?lang=en, 2024. (Accessed 28 March 2025).
- [20] Terna, Dati Statistici sull'Energia Elettrica in Italia 2022, 2023.
- [21] A. Delle Monache, B. Marmioli, N. Luciano, M.L. Carvalho, P. Girardi, G. Dotelli, S. Franzò, Influence of thermoelectric generation primary data and allocation methods on life cycle assessment of the electricity generation mix: the case of Italy, in: N.S. Caetano (Ed.), *Sustain. Dev. Renew. Energy*, Springer Nature Switzerland, Cham, 2024, pp. 417–428, https://doi.org/10.1007/978-3-031-54394-4_33.
- [22] MEES, Italian Ministry of Environment and Energy Security, National Energy Situation Report 2022. <https://www.mase.gov.it/notizie/energia-mase-pubblica-1-a-relazione-sulla-situazione-energetica-nazionale-2022>, 2022. (Accessed 28 March 2025).
- [23] GSE, Rapporto Statistico 2018, Fonti rinnovabili. https://www.gse.it/documenti_site/Documenti%20GSE/Rapporti%20statistici/GSE%20-%20Rapporto%20Statistico%20FER%202018.pdf, 2019.
- [24] VDMA, International Technology Roadmap for Photovoltaics (ITRPV), VDMA Photovoltaic Equipment, 2024. <https://www.vdma.org/international-technology-roadmap-photovoltaic>. (Accessed 28 March 2025). <https://www.vdma.org/international-technology-roadmap-photovoltaic>.
- [25] E. Commission, EU Reference Scenario 2020 - European Commission. https://energy.ec.europa.eu/data-and-analysis/energy-modelling/eu-reference-scenario-2020_en, 2021. (Accessed 28 March 2025).
- [26] European Commission, Handbook on the external costs of transport. <https://doi.org/10.2832/27212>, 2019.
- [27] Environmental Protection Agency, EPA Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances, Environmental Protection Agency, Washington, DC, USA, 2023.
- [28] P. Bickel, R. Friedrich, European Commission. *Externes – Externalities of Energy: Methodology 2005 Update*, Publications Office, Luxembourg, 2005.
- [29] European Commission, Trinomics, Energy Costs, Taxes and the Impact of Government Interventions on Investments: Final Report, Summary, Publications Office, LU, 2020. <https://data.europa.eu/doi/10.2833/827631>. (Accessed 24 March 2025).
- [30] J. Lu, C. Wang, C. Zhang, H. Guan, M. Skare, J. Streimikis, Avoided external energy costs due to penetration of renewables: evidence from Baltic States, *J. Environ. Manag.* 296 (2021) 113247, <https://doi.org/10.1016/j.jenvman.2021.113247>.
- [31] P. Ghisellini, R. Passaro, S. Ulgiati, Environmental assessment of multiple “cleaner electricity mix” scenarios within just energy and circular economy transitions, in Italy and Europe, *J. Clean. Prod.* 388 (2023) 135891, <https://doi.org/10.1016/j.jclepro.2023.135891>.
- [32] C. Ferrara, B. Marmioli, M.L. Carvalho, P. Girardi, Natural gas supply in Italy in 2030: a Life Cycle Assessment, in: 11th Int. Conf. Energy Environ. Res. Renew. Energy Decarbonization, International Society for Environmental Information Sciences and School of Engineering (ISEP) of the Polytechnic of Porto, 2024. Coimbra, Portugal.
- [33] R. Frischknecht, P. Stolz, L. Krebs, M. de Wild-Scholten, P. Sinha, Life Cycle Inventories and Life Cycle Assessment of Photovoltaic Systems, vol. 12, Int. Energy Agency IEA PVPS Task, 2020. Report IEA-PVPS T12-19, <https://iea-pvps.org/wp-content/uploads/2020/12/IEA-PVPS-LCI-report-2020.pdf>.
- [34] P. Saosee, B. Sajjakulnukit, S.H. Gheewala, Environmental externalities of wood pellets from fast-growing and para-rubber trees for sustainable energy production:

- a case in Thailand, *Energy Convers. Manag.* X 14 (2022) 100183, <https://doi.org/10.1016/j.ecmx.2022.100183>.
- [35] B.K. Sovacool, J. Kim, M. Yang, The hidden costs of energy and mobility: a global meta-analysis and research synthesis of electricity and transport externalities, *Energy Res. Social Sci.* 72 (2021) 101885, <https://doi.org/10.1016/j.erss.2020.101885>.
- [36] G.A. Thopil, A. Pouris, Aggregation and internalisation of electricity externalities in South Africa, *Energy* 82 (2015) 501–511, <https://doi.org/10.1016/j.energy.2015.01.059>.
- [37] S. Karkour, Y. Ichisugi, A. Abeynayaka, N. Itsubo, External-Cost estimation of electricity generation in G20 countries: case Study using a global life-cycle impact-assessment method, *Sustainability* 12 (2020) 2002, <https://doi.org/10.3390/su12052002>.
- [38] D. Streimikiene, I. Alisauskaite-Seskiene, External costs of electricity generation options in Lithuania, *Renew. Energy* 64 (2014) 215–224, <https://doi.org/10.1016/j.renene.2013.11.012>.
- [39] H. Yousefi, R. Habibifar, A. Farhadi, S.M. Hosseini, Integrated energy, cost, and environmental life cycle analysis of electricity generation and supply in Tehran, Iran, *Sustain. Cities Soc.* 97 (2023) 104748, <https://doi.org/10.1016/j.scs.2023.104748>.
- [40] T. Sterner, J. Ewald, E. Sterner, Economists and the climate, *J. Behav. Exp. Econ.* 109 (2024) 102158, <https://doi.org/10.1016/j.socec.2023.102158>.
- [41] C. Azar, J.G. Martín, D.Ja Johansson, T. Sterner, The social cost of methane, *Clim. Change* 176 (2023) 71, <https://doi.org/10.1007/s10584-023-03540-1>.
- [42] A. Molocchi, Valuing the social cost of carbon: do economists really care about climate change? *Econ. Pol. Energy Environ.* (2023) 41–76, <https://doi.org/10.3280/EFE2023-002003>.
- [43] Interagency Working Group on the Social Cost of Carbon of the US Government, *Social Cost of Carbon for Regulatory Impact Analysis*, 2010.
- [44] National Academy of Sciences Engineering Medicine, Valuing Climate Damages, Updating Estimation of the Social Cost of Carbon, 2018, <https://doi.org/10.17226/24656>.
- [45] USEPA, The social cost of Green House gases, estimation codes and replication files. <https://github.com/USEPA/scghg>, 2025. (Accessed 27 February 2025).
- [46] IWG, Interagency Working Group on Social Cost of Carbon, Technical Support Document: Social Cost of Carbon, Methane, and Nitrous Oxide: Interim Estimates Under Executive Order 13990, United States Government, 2021. https://www.whitehouse.gov/wpcontent/uploads/2021/02/TechnicalSupportDocument_SocialCostofCarbonMethaneNitrousOxide.pdf. (Accessed 2 April 2025). https://www.whitehouse.gov/wpcontent/uploads/2021/02/TechnicalSupportDocument_SocialCostofCarbonMethaneNitrousOxide.pdf.
- [47] K. Rennert, F. Errickson, B.C. Prest, L. Rennels, R.G. Newell, W. Pizer, C. Kingdon, J. Wingenroth, R. Cooke, B. Parthum, D. Smith, K. Cromar, D. Diaz, F.C. Moore, U. K. Müller, R.J. Plevin, A.E. Raftery, H. Ševčíková, H. Sheets, J.H. Stock, T. Tan, M. Watson, T.E. Wong, D. Anthoff, Comprehensive evidence implies a higher social cost of CO₂, *Nature* 610 (2022) 687–692, <https://doi.org/10.1038/s41586-022-05224-9>.
- [48] R.S.J. Tol, Social cost of carbon estimates have increased over time, *Nat. Clim. Change* 13 (2023) 532–536, <https://doi.org/10.1038/s41558-023-01680-x>.