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Integrated hybrid multi-regional input-output for assessing life cycle air emissions of the Italian power system

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ABSTRACT

The air emissions of the Italian power system, as well as national emissions between 2010 and 2017 and projections to 2040, have been assessed from a lifecycle perspective, using an integrated hybrid two-region input-output model of Italy versus the rest of the world. The Italian economy is divided into 42 sectors, including electricity, which is further disaggregated into seven technologies. Detailed electricity sector data, from Istat, are fed into the EXIOBASE input-output database. NAMEA tables represent overall air emissions, while the Ecoinvent database is used for the electricity sector. Electricity transition scenarios from Terna and Snam have been integrated into input-output and air emission databases. Demand and emissions were tracked within the electricity sector over medium-term, and the findings showed a sharp decrease between 2017 and 2025, from 97.5 $MtCO_2$ to 32.6 $MtCO_2$. By 2040, air emissions from the electricity sector are expected to grow gradually, compared to those of 2030, from 22.2 $MtCO_2$ to 25.9 $MtCO_2$, suggesting that the demand between 2030 and 2040 grows faster than the decarbonization effort during the same period. There is an overall, gradual downtrend between 2010 and 2040, with all air emission categories declining by half from both production and consumption-based perspectives in this period.

1. Introduction

Rising temperatures and other adverse consequences of climate change require a comprehensive socio-economic transition, especially in the energy sector, due to its significant contribution to global greenhouse gas (GHG) emissions. There is a strong global energy transition toward renewable energy sources (RES), improving energy efficiency and a process of electrification, concerning both the supply of energy and the demand sectors of industries, building and transportation sectors. Several energy transition scenarios have been developed by the International Renewable Energy Agency on energy production and consumption [1], and the International Energy Agency on energy in buildings [2].

The purpose of the energy transition scenarios aim at decarbonizing the energy sector and keeping global temperature rise below 2 °C, which align with the goal of carbon neutrality by 2050, as outlined in the European Green Deal [3]. These scenarios require hybrid tools which are capable of evaluating the path of decarbonization on a large scale, and to take into account both the energy sector and other economic sectors. Moreover, the GHG reductions of the renewable energy technology adoption should be considered with a life cycle thinking approach, extending beyond the operation stage of the technologies to encompass their entire life cycle.

The energy sector constitutes three-quarters of global GHG emissions [4,5]. The heat and electricity sector alone contributed about 42 % of the energy sector's GHG emissions globally [6]. Besides, the energy sector is a significant source of nitrogen oxides (NO_x), sulphur oxides (SO_x) and particulate matter (PM) [7]. Due to the large contribution of the energy sector particularly electricity generation, to the total GHG and other air emissions, these sectors should be prioritized to reduce global emissions.

Electricity sector air emissions should be considered under both production (PBA) and consumption-based accounting (CBA) perspectives with the life cycle thinking approach. Current GHG reporting systems, such as those of United Nations Framework Convention on Climate

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Nomenclature

CBA	Consumption-based accounting
CH_4	Methane
CO_2	Carbon dioxide
CSP	Concentrating solar power
EEIOA	environmentally extended input-output analysis
GHG	Greenhouse gas
H-MRIO	Hybrid multi-regional input-output analysis
HFC	Hydrofluorocarbon
IOA	Input-output analysis
IOT	Input-output table
LCA	Life cycle assessment
LCI	Life cycle inventory
MRIO	Multi-regional input-output analysis
N_2O	Nitrous oxides
NACE	Classification of economic activities of European Community
NAMEA-Air	National Accounting Matrix with Environmental Accounts Air Emissions
NMVOC	Non-methane volatile organic compound
NOx	Nitrogen oxides
PBA	Production-based accounting
PFC	Perfluorocarbon
PM	Particulate matter
RES	Renewable energy resource
RoW	Rest of the world
SF_6	Sulphur hexafluoride
SOx	Sulphur oxides

Change and Convention on Long-range Transboundary Air Pollution, require countries to report on their annual GHGs as well as other air emissions, using a PBA perspective and following the so-called “territorial” principle. This accounting principle records emissions based on their physical sources, arising from the territory of a given country regardless of who emits. Its limitation is the omission of emissions embodied in trade, import and export. This raises the question of emission responsibility, borne either by the producing or the consuming entities. Both perspectives are useful in policymaking, and may lead to distinct, yet complementary decisions. For example, CBA covers blind spots of PBA, such as carbon leakage phenomena in highly-connected countries. On the methodological side, however, complementing PBA with CBA drives the need for a more diverse accounting method.

This study quantifies and assesses air emissions of Italy, focusing on the Italian electricity sector projections from both PBA and CBA perspectives between 2010 and 2040. By considering life cycle air emissions of the Italian electricity sector, three specific aspects will be examined: (1) what makes up of the changes in Italian air emission in the period 2010–2017 and projections to 2040; (2) how the air emissions of the Italian electricity sector are impacted by other economic sectors and vice versa; and (3) what are the relations between the air emissions embodied in trade and consumption activities, and their implications on air emission reduction efforts.

This study contributes to the methodological aspects of environmental accounting by filling the literature gap of computing sectorial and national air emissions from both PBA and CBA perspectives with a life cycle thinking approach, and helps to guide policy decisions. At the same time, the study provides a case study on the Italian electricity transition scenarios to examine the changes in sectorial and national air emissions between 2010 and 2017, and projections to 2040; and identify the interactions among air emissions of different economic sectors, in relations with imports and exports.

Methods for life cycle GHG and air emission accounting include process-based life cycle assessment (LCA) [8], environmentally extended input-output analysis (EEIOA) [9] and hybrid approach of LCA and input-output analysis (IOA) [10]. EEIOA was developed as an additional layer to economic IOA, the principal objective of which is quantifying direct and indirect input requirements to meet a given final demand. The product system is thereby considered from a top-down point of view, starting from the whole economic supply chain, and narrowing it down into economic sectors and product groups. In EEIOA, both direct and indirect emissions of the consumed product groups are quantified and compared among different categories of household consumption, investment or export [11,12].

The choice of different LCA modelling approaches, with different sources of data and allocation practice, is a source of uncertainty during the quantification and assessment of the product system [13]. LCA with the process-based inventory data can provide product-level details, but may introduce truncation errors due to the exclusion of some processes or system incompleteness. For example, a case study on copper wire indicates that the system boundary gap of LCA may cause up to 60 % of truncation error [14]. This occurs because some processes are excluded during different supply chain tiers [15]. On the other hand, EEIOA presents an economic-wide view and does not require allocation practice, but may cause aggregation errors during the grouping of several products into a single sector. The complexity of the supply chain causes challenges in identifying an appropriate system boundary, which suggests the need for an integrated hybrid approach for GHG and air emission accounting [16].

IOA (and EEIOA) traces economic (and environmental) flows within a nation or a region, without considering international trade. Multi-regional input-output (MRIO) analysis extends the boundary to include several regions or nations, incorporating import and export flows among them [17,18]. This feature allows addressing questions related to countries’ responsibilities. For example, a country that is highly dependent on imported resources, that are more energy- or emission-intensive than their local counterparts, would not be incentivized to develop local industry if only territorial emissions are accounted for – even though it would decrease global emissions. Another question is how to effectively reduce energy consumption or mitigate emissions at the international level. Therefore, instead of hybridizing LCA and IOA, the hybridization is conducted on LCA and MRIO, which will be called “H-MRIO” in this paper.

Integrated hybrid analysis has been applied for quantifying the life cycle impacts of electricity generation technologies as well as in other sectors such as energy consumption in buildings [19], construction materials [20], transportation [21], national import [22] and cities [23]. In the electricity sector, Gibon et al. used the H-MRIO approach to integrate energy scenarios in an MRIO table to assess the life cycle GHG emissions of concentrating solar power (CSP) [24]. The model is a combination of process-based life cycle inventory (LCI) and MRIO tables with forecasted technological and resource changes up to 2050. It was found that life cycle GHG emissions of CSP varied between 33 and 95 gCO_2e/kWh (depending on specific regions) in 2010 and would reduce to 30–87 gCO_2e/kWh in 2050.

Similarly, a H-MRIO model was proposed in China by Li et al. to evaluate the life cycle CO_2 emissions, energy consumption and energy payback time of a 10-MW CSP plant [25]. Vélez-Henao and Vivanco conducted a H-MRIO study on wind power plants, using on-site data for direct emissions and supply chain data for indirect emissions [26].

Different electricity technologies and various life cycle impacts were extended in Hertwich et al.’s study, which investigated the co-benefits and trade-offs of decarbonizing the electricity sector in terms of life cycle GHG and non-GHG impacts [27]. At global scale, Wan et al.

studied the direct and indirect impacts of water consumption from power mix adjustment in the world largest seven emitting economies [28]. In de Koning's study, a MRIO database (EXIOBASE) was used to calculate CO_2 emissions of production activities to meet final demand by 2050 [29]. The author developed several scenarios taking into account socio-economic development, efficiency and technology improvement, low-carbon energy technologies and shifts in production and consumption. The study concluded that it is difficult to reach the 2 °C reduction targets relying on low-carbon energy technologies alone.

It is worth noting that the number of H-MRIO studies remains somewhat limited. Existing literatures applied H-MRIO either on individual power technologies or on an electricity mix. The studies conducted on electricity mix, e.g. Refs. [27–29] considered the global emissions as a whole. Therefore, this study aims to contribute to H-MRIO literature on the electricity sector by integrating power development scenarios and analysing the sectorial and national emissions from a global perspective. Main points of the existing literature applied integrated H-MRIO in the energy sector are presented in Table 1.

This study utilized the H-MRIO approach for quantifying and assessing the life cycle GHG and other air emissions of Italy and its electricity sector, taking into account of the electricity transition scenarios. The national and sectoral air emissions are considered from both PBA and CBA perspectives, including imports to and exports from Italy and their relationship with the air emissions from the rest of the world (RoW). The ultimate goal of the study is to support energy, economic and environmental policies in reducing the national air emissions from power consumption and production, considering trade dynamics, and avoiding transferring the impacts of one sector or country to another.

2. Methodology

2.1. Conceptual framework

The H-MRIO is applied following the under-described framework (illustrated in Fig. 1).

(1) First, two types of data, including MRIO and hybridization data are collected. MRIO data such as the Italian and multi-regional input-output tables (IOTs) and air emissions accounts are collected from Istat and EXIOBASE. Hybridization data is collected from Italian electricity/energy suppliers [30] for power development scenarios, and from the Ecoinvent database for direct air emissions of electricity generation technologies.
(2) From MRIO data, the MRIO model with two regions of Italy and RoW and 36 economic sectors will be constructed.
(3) In combination with the power development scenarios, the Italian electricity sector is disaggregated into seven electricity generation technologies, for both intermediate flow matrices and final demand vectors in Italian IOT. Similarly, in the stressor matrices, the air emissions of the electricity sector are disaggregated into those of seven electricity generation technologies, with data taken from Ecoinvent. At this time, the H-MRIO model consists of 42 sectors (36 economic sectors - 1 electricity sector + 7 power technologies).
(4) The model is calculated with historical data of 2010 and 2017, and replicated for the future scenarios of 2025, 2030 and 2040.

Table 1
Main points of the existing literature applied integrated H-MRIO in the energy sector.

Paper	Studied product	Geographical boundary	Impacts
[24]	One technology (CSP)	Global	Life cycle GHG emissions
[25]	One technology (CSP)	Country (China)	Life cycle CO_2 emissions, energy consumption and energy payback time
[26]	One technology (Wind)	Country (Columbia)	Several life cycle environmental impacts, including climate change, eutrophication, acidification, toxicity, etc.
[27]	Several electricity technologies	Global	Various life cycle impacts, including GHG and non-GHG impacts
[28]	Global electricity mix	Global	Direct and indirect impacts of water consumption
[29]	Low carbon technologies	Global	CO_2 emissions

The hybridization and MRIO calculation procedures are written in the Python language, provided in the Supplementary Information. The mathematical framework and specific data for H-MRIO analysis are presented below.

2.2. H-MRIO mathematical framework

The calculations of life cycle requirements, as well as associated impacts (here, air emissions) are carried out following Leontief equations (1)–(4) for IOA and EEIOA.

Production-consumption balance

$$Ax + y = x \tag{1}$$

Solving the balance equation

$$x = (I - A)^{-1} y = Ly \tag{2}$$

Calculating (direct) stressor coefficients

$$S = F\hat{x}^{-1} \tag{3}$$

Calculating life cycle multipliers

$$M = SL \tag{4}$$

In which:

x is the vector of total gross outputs of the economy needed to meet the final demand, dimension n*1.

I is the identity matrix, A is the intermediate flow coefficient matrix, dimension n*n.

L is the Leontief matrix, dimension n*n

y is the vector of final demand of products, dimension n*1.

S is the stressor coefficients matrix, dimension m*n.

F is the stressor matrix, dimension m*n.

M is the multiplier matrix.

In a multi-regional context, the life cycle emissions of the PBA and CBA of region i, F^i_{pba} and F^i_{cba} can be expressed in equations (4) and (5):

$$F^i_{pba} = F^i_s e + F^i_y \tag{4a}$$

$$F^i_{cba} = My^i + F^i_y \tag{5}$$

In which:

F^i_{pba} is the life cycle emission of the production-based accounts of region i

F^i_s is the direct emission from production activities of region i, and e an appropriate summation vector

F^i_y is the direct emission from consumption activities of region i

F^i_{cba} is the life cycle emission of the consumption-based accounts of region i

M and y^i are the multiplier matrix and the vector of final demand of region i

With the inclusion of power development scenarios, the H-MRIO model is adapted following the THEMIS model [24]. THEMIS model provided the global perspective, while this H-MRIO estimated and assessed the national emissions from domestic, import and export

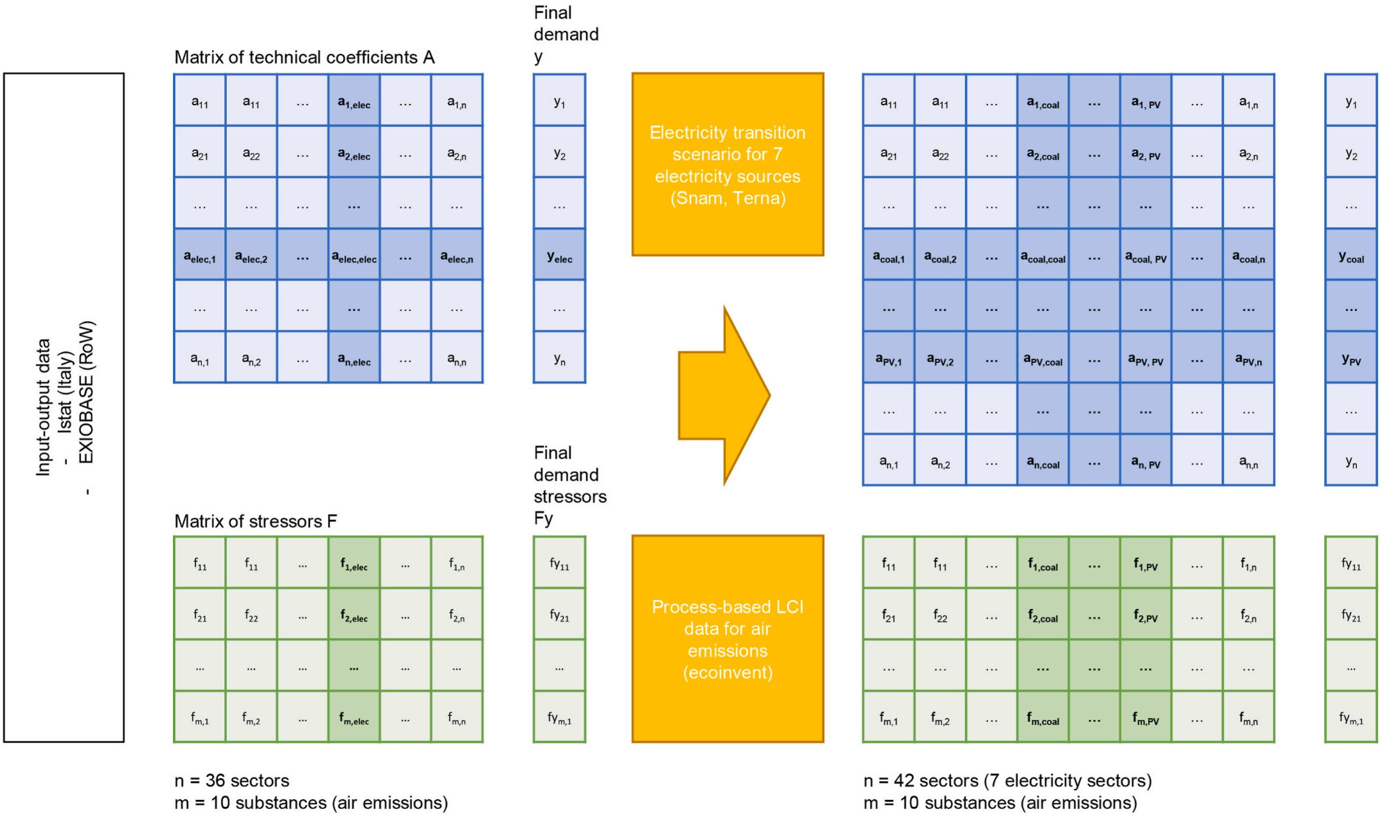


Fig. 1. Main principles of the disaggregation, and integration of energy scenarios.

activities. The hybrid process is implemented for each matrix and vector, including the technical coefficient matrix A, final demand vector y and stressor matrix F. An example of hybridization of matrix A for the energy sector is presented in equation (6):

$$A_{t-ele} = \widehat{v}_{t-es}^{T} * A_{2017-ele} * v_{t-es} \tag{6}$$

In which:

A_{t-ele} is the disaggregated matrix of the electricity sector in year t

$A_{2017-ele}$ is the original vector of the electricity sector in 2017

v_{t-es} is the vector of electricity share in year t

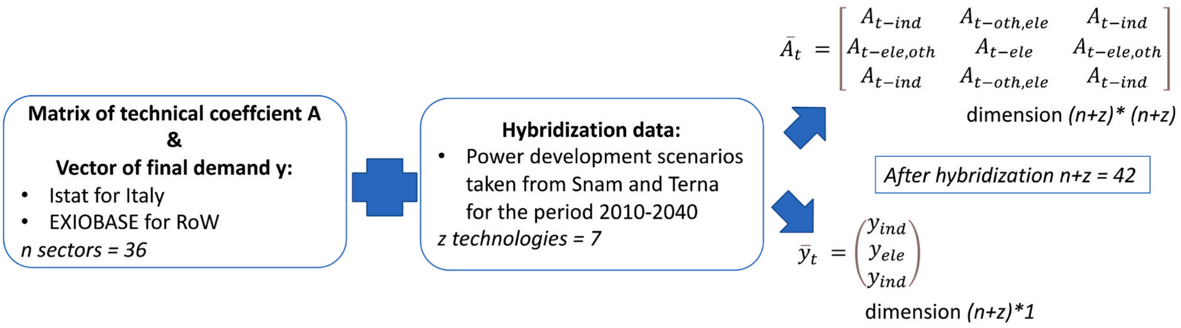
$\widehat{v}_{t-es}^{T}$ is the transpose vector of v_{es}, $\widehat{v}$ is the diagonal matrix with the principal diagonal elements being taken from vector v

Further information on the hybridization equations for each matrix and vector can be seen in the supplementary information, Fig. 2 for hybridizing the matrix A, the vector y, and Fig. 3 for hybridizing the matrix F.

2.3. Data

2.3.1. Intermediate flow coefficient matrix

The intermediate flow coefficient matrix A presents the relationship among different industries (or sectors) of the economy, in which products (or outputs) of one industry are used as inputs of other industries, or in other words, they indicate the inter-industrial relations of the amount of intermediate products to produce other products. The matrix A is developed based on the Italian IOT for the year 2017 [31]. For the matrix A in future scenarios, the data is taken from IOT with the integration of power development scenarios by 2025, 2030 and 2040. The Italian IOTs are published every five years by Istat, with a breakdown of the economy into 63 industrial sectors, corresponding to 63 products. The sectors and products are classified by activity, with reference to the classification of economic activities of European Community (NACE). The coding structure of CPA corresponds to that of NACE up to the fourth level [32].



$$\bar{A}_t = \begin{bmatrix} A_{t-ind} & A_{t-oth,ele} & A_{t-ind} \\ A_{t-ele,oth} & A_{t-ele} & A_{t-ele,oth} \\ A_{t-ind} & A_{t-oth,ele} & A_{t-ind} \end{bmatrix}$$

$$\bar{y}_t = \begin{pmatrix} y_{ind} \\ y_{ele} \\ y_{ind} \end{pmatrix}$$

Fig. 2. Hybridization of matrix A and vector y.

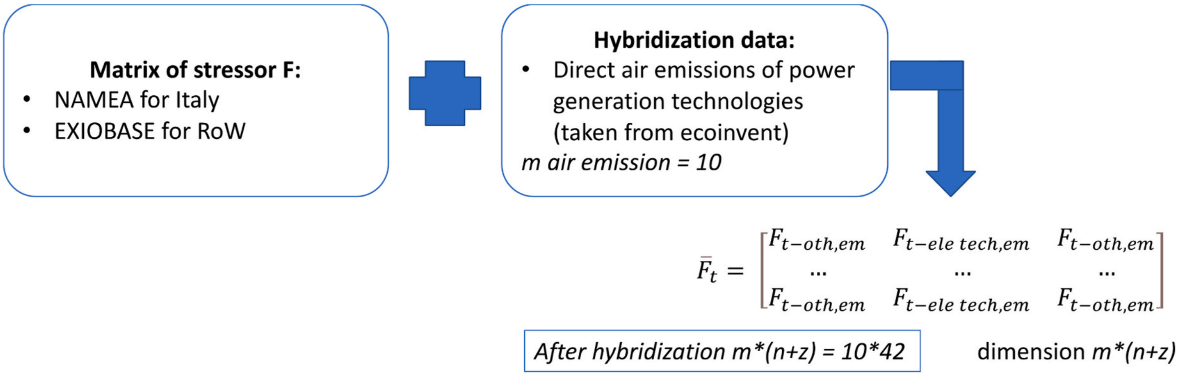


Fig. 3. Hybridization of matrix F.

2.3.2. Power development scenarios

This section describes the Italian electricity generation technologies in 2017 and its development pathway by 2040. According to the data of the National Trend Italy developed by Terna and Snam [30], the Italian power technologies in 2017 comprised of (1) natural gas-based power, (2) coal and other fossil fuel-based power, (3) hydropower, (4) wind power, (5) solar power, and (6) other RES-based power. By 2025–2040, the generation mix will change towards decreasing of fossil fuels and increasing of RES. These scenarios of Snam and Terna are adapted to the electricity sector for the hybridization of the matrix A. Fig. 4 below indicates the percentage of six electricity generation technologies along with net import/export (which is considered as the seventh technology) contributing to the grid mix between 2010 and 2040.

This power development scenario will be integrated into the Italian IOT. However, in the Italian IOT, the electricity, gas and steam sector are presented as one single product, encompassing three subsectors: electricity supply, gas supply, and steam and air conditioning supply, not limited to electricity generation alone. Among these subsectors, electricity generation represents 82.4 % of the sectoral value added in 2017 [33]. Therefore, it is assumed that electricity generation technologies can be the representative of the electricity, gas, and steam sector.

2.3.3. Final demand vector

IOTs present the link between the inputs used and outputs manufactured by the production sectors, and the final demand (y vector). In this study, data on final demand, extracted from the Italian IOT for 2017 are utilized for vector y_{2017}. The total final demand of 2025, 2030 and 2040 (y_{2025}, y_{2030}, y_{2040}) is forecasted based on the total final consumption data of Organisation for Economic Co-operation and Development's studies estimated for 2023 [34], using linear regression. The details of final consumption for each economic sector are estimated based on the average share of final consumption during the period 2015–2017. Besides, it is essential to disaggregate the final demand from the electricity sector into final demand of specific electricity generation technology, using the production share of the technologies.

2.3.4. Stressor coefficient matrix

The stressor coefficient matrix S indicate the stressor F per total gross output x of the economy. The data set for the matrix F in 2017 was taken from the National Accounting Matrix with Environmental Accounts Air Emissions (NAMEA-Air) of Italy. The Italian NAMEA-Air tables are published annually by Istat [35], presenting 10 atmospheric emission categories, namely CO_2, CH_4, N_2O, SO_x, NO_x, NH_3, CO, NMVOC, $PM_{2.5}$ and PM_{10} for 63 products (production sectors) and three household consumption activities of transport, heating and others [35].

The NAMEA-Air shares the same framework and similar classification with IOT, with 63 industries/sectors. In NAMEA-Air, the emissions of the electricity sector are not further divided into specific electricity generation technologies. Therefore, they are disaggregated into seven electricity generation technologies using the data set from Ecoinvent for air emissions of electricity generation technologies [36]. It should be noted that the emissions of Ecoinvent data is more diverse than that of NAMEA-Air. Therefore, the two databases need to be matched. The matching rules follow the description on the coverage of substances of NAMEA-Air [37].

Matrix F of future years (F_{2025}, F_{2030}, F_{2040}) is forecasted using linear regression. In this case, the emission volume of the economy undergoes a gradual change during the period 2017–2040 due to economic development, productivity, and efficiency improvement.

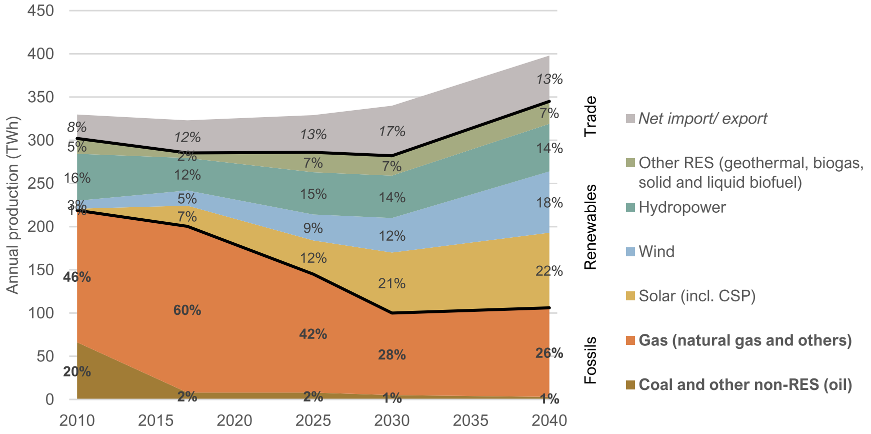


Fig. 4. National trend electricity production scenario for Italy, 2010–2040, fossils are indicated in bold, imports in italics [30].

2.3.5. Aggregation of economic sectors

To construct the 2-region MRIO table, data for the first region, Italy is extracted from Istat, and RoW is added as the second region, with data taken from EXIOBASE database. Instead of using EXIOBASE directly for both Italy and RoW, the study used Istat data for Italy and EXIOBASE for RoW. This decision increases the workload of matching two databases.

EXIOBASE is a multi-regional environmentally extended supply-use table and IOT available for the years 1995–2011, covering 49 countries and regions (28 EU members, 16 major economies and five RoW regions). The IOTs are built upon the supply-use table of 163 industries and 200 products, illustrating the structural change by integrating economic development as reported by national statistics agencies. The data is detailed for energy, agricultural production, resource extraction and bilateral trade [38]. Until now, the database is now-casted to 2022 and the most updated version is EXIOBASE 3.8.2 (Stadler et al., 2021).

The classification of industries and products in the EXIOBASE is based on NACE1. The classification of industries and product in Istat data (for both IOTs and air emission accounts) were based on NACE1 until 2010. After 2010, the classification changed into NACE2. Besides, the number of Istat economic sectors is 63 and that of EXIOBASE is 200 (product by product). The mismatch in sector classification (and number) between the Italian and RoW databases requires a common concordance to match in these two databases' economic sectors. In this study, the economy is firstly aggregated into 36 production sectors and later disaggregated into 42 sectors. The aggregation and disaggregation of economic sectors in different databases can be seen in the supplementary information.

3. Results and discussion

3.1. Decomposition of Italian consumption-based emissions

The total GHG emissions to meet global final demand in 2017 calculated with this model is 47.69 $GtCO_2e$. This number is slightly higher than the global GHG emissions estimated by Climate Watch, at 47 $GtCO_2e$ excluding land use change and forestation [4]. The difference in the obtained results of this model and other models was caused by the difference in the scope of air emissions being studied. This model has been developed based on Istat database for Italy and EXIOBASE data for RoW. Both Istat and EXIOBASE databases are actual anthropogenic emissions of CO_2, CH_4 and N_2O, excluding emissions from land use land use change and forestation, and biomass burning as a fuel. Meanwhile, the Climate Watch's model takes into account all GHGs (CO_2, CH_4, N_2O, and F-gases such as HFCs, PFCs, and SF_6), excluding land use change and forestation. This causes a difference of around 1 $GtCO_2e$ of F-gases and 2.8 $GtCO_2e$ of CH_4. Moreover, Climate Watch's model excludes short-cycle biomass burning such as agricultural waste burning and savanna burning, but includes other biomass burning such as forest fires, post-burn decay, peat fires and decay of drained peatlands. The exclusion of emissions from land use (mostly CH_4), biogenic CO_2 and F-gases in this model leads to an insignificant difference of around 0.69 $GtCO_2e$ (less than 1.5 %).

Another calculation with this model for GHGs from combustion activities only, and excluding fugitive emissions of CH_4, GHG emissions from agriculture, waste management and industrial production, indicated that the GHG emissions to meet global final demand in 2017 is at 33.96 $GtCO_2e$. In this case, the GHG emissions from combustion account up to 70 % of the total GHG emissions. This result is 3.1 % higher than the reported number of the International Energy Agency on CO_2 emissions for the energy sector in 2017, at 32.92 $GtCO_2e$ [39,40].

In order to look into details of the sources of the change in the air emission, a decomposition analysis has been conducted following [41]. A similar study on air emission change in Italian household consumption between 1999 and 2006 [42] shows that, between 1999 and 2006, the indirect CO_2 emission from Italian household consumption was about 13 $MtCO_2$.

With the change in final demand and electricity sector composition of Italy, consumption-based GHG emissions appear to decrease in the period 2010–2040 (Fig. 5). Specifically, due to changes in production structure, emission coefficients, and final demand, the annual CO_2 emission reduction embodied in production activities during the period 2017–2025 will be up to 7.1 $MtCO_2$, which makes up 57.1 $MtCO_2$ emission reduction in the whole period. The increased final demand of Italy causes an annual increase of 4.8 $MtCO_2$. The change in the production structure, including the electricity sector and corresponding change in other economic sectors, helps to reduce 6.1 $MtCO_2$ annually. The change in emission flow coefficients brings an annual reduction credit of about 5.8 $MtCO_2$. During the period of 2025–2030 and 2030–2040, the annual change in emission reduction will be much smaller, at 2.3 $MtCO_2$ and 33.9 $ktCO_2$, respectively.

3.2. Change in air emissions of Italian electricity sector

The hybridization of power development scenarios causes a change in all air emissions categories in 2017, at various scales. The smallest difference occurs in CO_2, at an 8 % difference. The largest difference occurs in $PM_{2.5}$, which is followed by SO_x. The difference in other air emissions: N_2O, CH_4, NO_x, NH_3, NMVOC, and PM_{10} ranges between −0.98 and 2.28. This difference is mainly caused by the level of aggregation of process-based LCI and input-output data. Input-output data is taken from NAMEA, which reports air emissions of the electricity, gas and steam sector, while LCI data includes air emissions of electricity generation technologies. First, this mismatch causes the omission of emissions from gas supply and steam and air supply in the LCI data used in this study. The production of natural gas is a CH_4-intensive process [43]. Therefore, the missing of emissions from gas supply in the LCI data will omit an amount of CH_4 emissions from this subsector, which explains the lower CH_4 emissions of hybrid results compared to the original NAMEA. Second, the air emissions of electricity generation technologies in LCI data are gathered for the seven 'representative' technologies contributing to most of the electricity generation. In practice, the number of 'actual' technologies goes beyond seven. The emissions are not the same for 'representative' and 'actual' technologies, which causes a difference between the hybrid results and the original input-output data.

After 2017, due to the change in electricity generation technologies and power consumption, the future air emissions dramatically reduce in the electricity sector, as presented in Fig. 6. Most of the PBA emissions of the electricity sector come from fossil fuel-based electricity, e.g., coal and natural gas. A smaller part comes from other RES, including geothermal and biomass-based electricity. The production of solar and wind power does not generate any airborne emission, and that of hydropower emits N_2O only. The reduction in electricity from fossil fuels such as coal and natural gas contributes to reducing the PBA emissions of this sector nearly four-fold from 97.5 $MtCO_2$ in 2017 to 25.9 $MtCO_2$ by 2040. With regards to CBA, CO_2 emissions total 34.9 $MtCO_2$ in 2017, and then drop by more than half, at 13.7 $MtCO_2$ by 2040. The CBA CO_2 emission of the electricity sector is divided among technologies by their production structure. As it can be observed, low-carbon technologies such as solar and wind power technologies contribute to emissions, because of the manufacturing of their infrastructures. The CBA emissions of electricity are smaller than the PBA ones, as they are shared by other economic sectors as intermediates for production activities. CBA takes into account the emissions of electricity as a final product, and excludes the emissions of electricity as an intermediate for other production activities.

3.3. Change in emissions of other Italian economic sectors by years

The absolute change in air emissions of the electricity sector induces a change in the economy emission structure, as presented in Fig. 7. In 2017, from PBA perspective, the electricity sector accounts for the

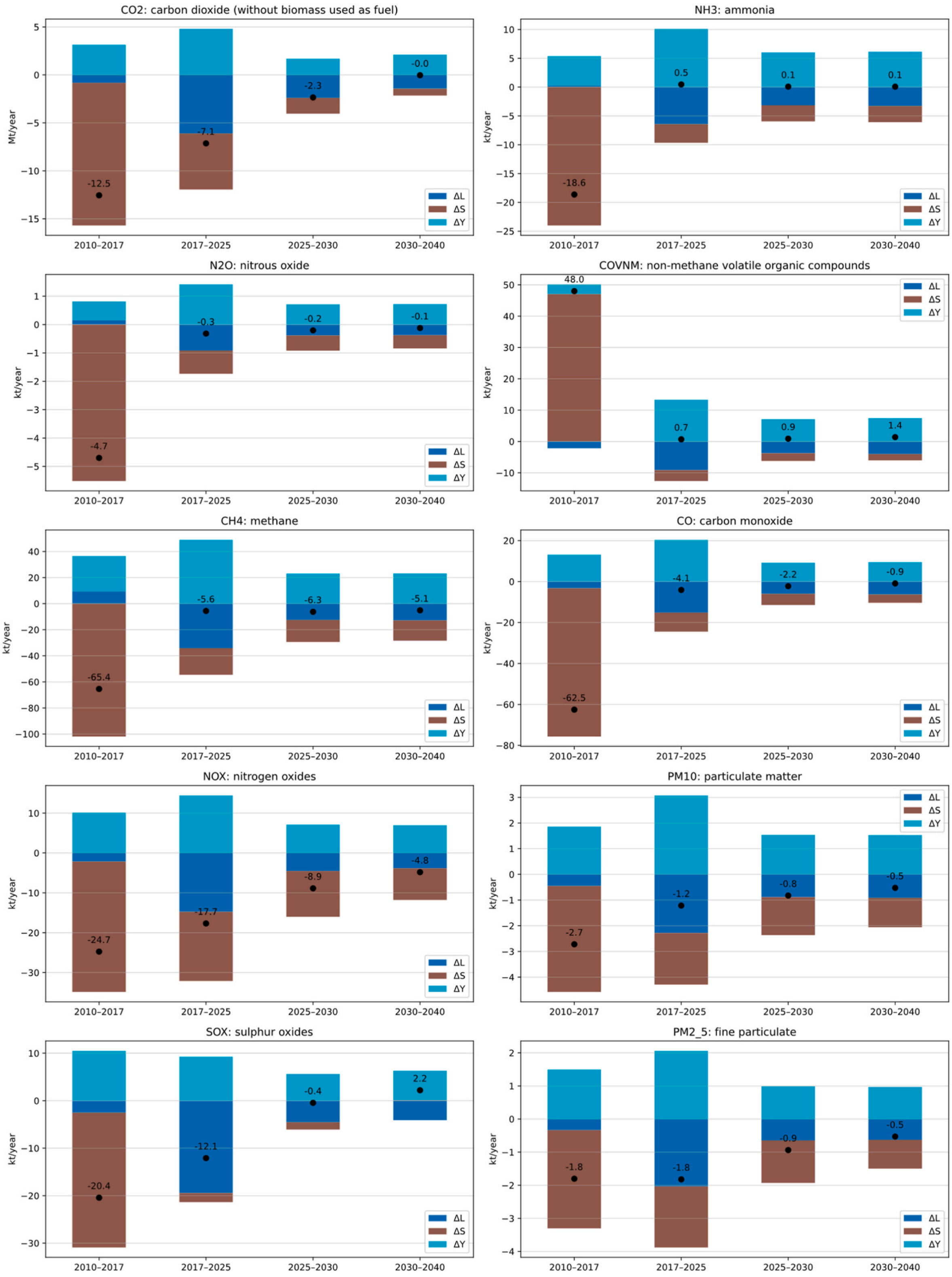


Fig. 5. Decomposition of the Italian consumption-based emission variation over four periods. Note: the periods are not of equal duration, variations are indicated as the average annual variation within each period.

largest share of the national emission of CO_2 (36 %), which reduces to 18 % by 2040. At the same time, the CO_2 emission shares of agriculture, forestry and fishing, wholesale and retail trade, water and waste management, and air transportation increase about 2–5% points each between 2017 and 2040. Some economic sectors, which have the smaller change in their CO_2 emission shares such as rubber and plastics, water transportation, coke and petroleum and land transportation (though their large contribution to the total emissions), reduce by 1% point during the same period. Apart from the electricity sector, other economic sectors see a considerable change in their emissions (absolute

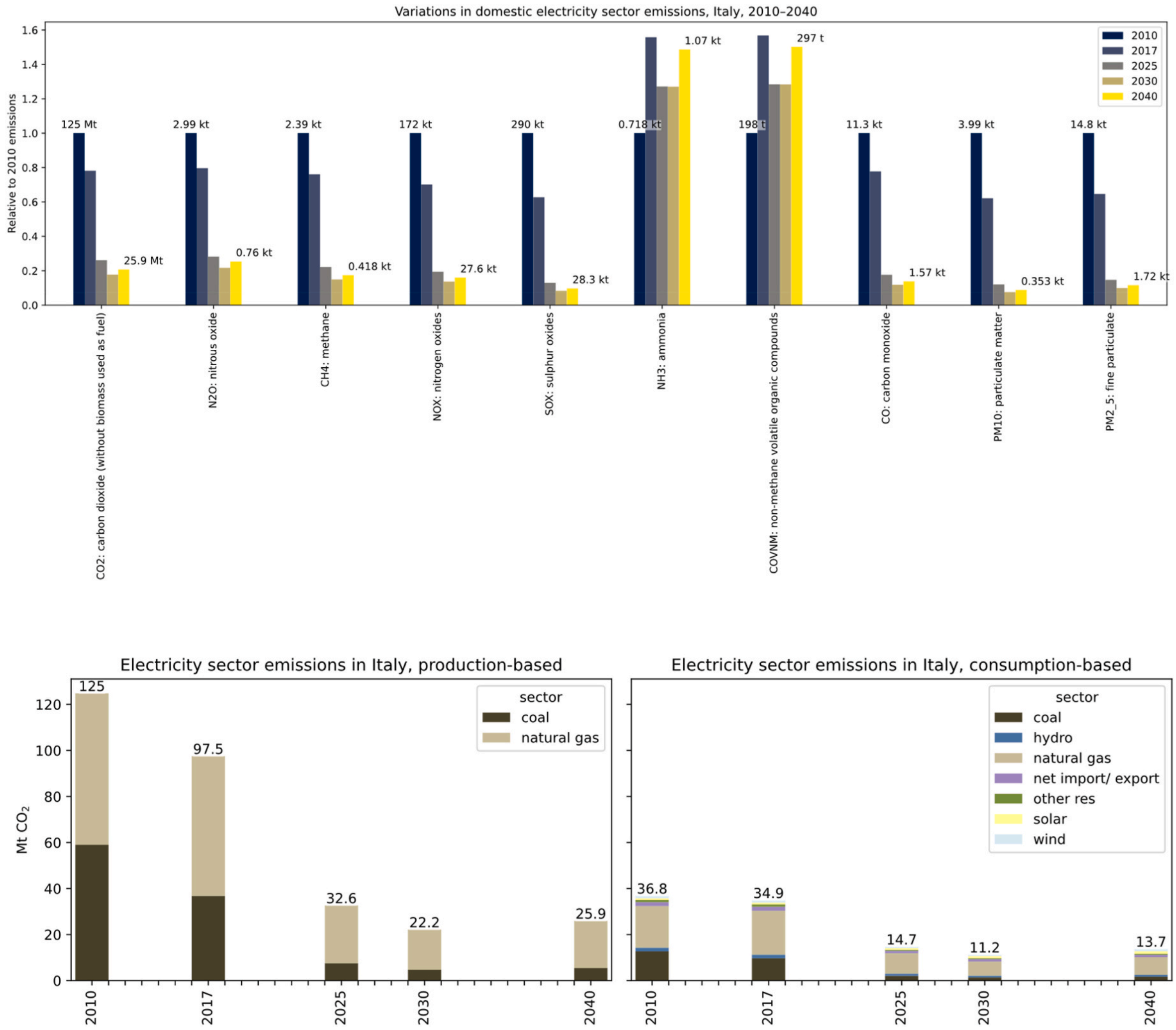


Fig. 6. Air emissions of the Italian electricity sector by year. Top: all air emissions, bottom left: production-based CO_2 emissions, bottom right: consumption-based CO_2 emissions.

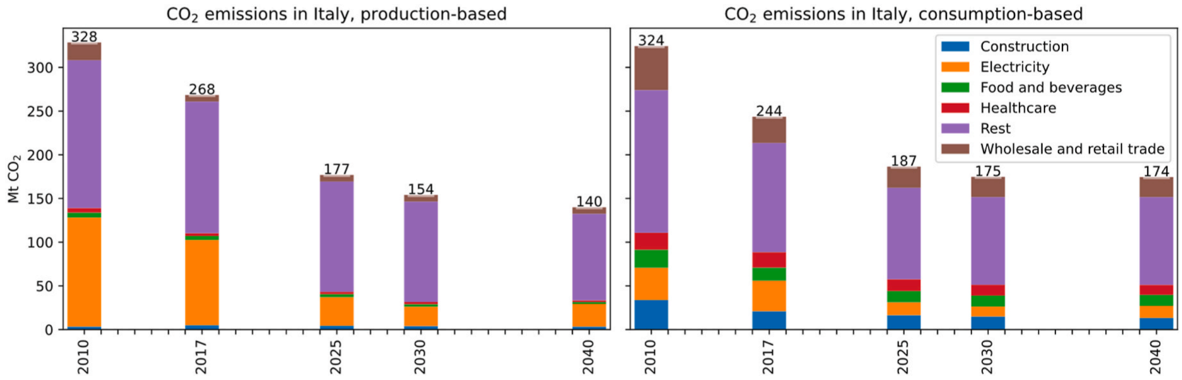


Fig. 7. Contribution of economic sectors to life cycle emissions (excluding import, export and trade).

value) during the period 2017–2040. For example, the CO_2 emissions of land transportation reduce from 15.64 $MtCO_2$ in 2017 to 10.57 $MtCO_2$ by 2040, 32 % in the whole period or 1.4 % annually.

From CBA perspective, the changes in electricity consumption induce changes in other economic sectors, which are clearly shown in coke and petroleum, pharmaceuticals, water transportation, education, and healthcare, either increasing or decreasing their emissions. Particularly, electricity sector accounts for 11.6 % of the total CO_2 emissions in 2017, which reduces to 5.9 % by 2040. The CO_2 emission shares of some other economic sectors also decrease during the period 2017–2040, such as construction and healthcare (reducing around 1% point). Meanwhile, the CO_2 emission shares of some sectors increase, such as food and beverage (increasing less than 1% point). It should be noted that the CO_2 emission contributions of these sectors to the national CBA emissions do not show the correspondingly absolute increase (or decrease). Instead, they relatively present the changes in the identified “hotspot” sectors over years.

The absolute values of the CO_2 emissions decrease in all economic sectors between 2017 and 2040. The decrease is clearly presented in economic sectors such as construction, decreasing from 20.99 $MtCO_2$ in 2017 to 13.4 $MtCO_2$ by 2040, at about 0.33 $MtCO_2$ annually; or food and beverage, decreasing from 15 $MtCO_2$ to 12.5 $MtCO_2$, or 0.1 MtCO2 annually; or healthcare, decreasing from 17.7 $MtCO_2$ to 11.43 $MtCO_2$ or 0.27 $MtCO_2$ annually in the same period (see Fig. 7).

3.4. Share of emissions embodied in import out of consumption

Emissions from imports account for a significant share of the national CBA emissions in most of air emission categories. Specifically, CO_2 emissions embodied in imports hold up to 43.9 % of CBA emissions. This indicates the outsourcing of Italian air emissions, as well as its emission dependency on foreign products. In order to reduce the emissions of Italy, it is necessary to take into account of imported products, and emissions of its trade partners. Emissions from some economic sectors are more dependent on those of imported products than others, which is expressed by the close or loose relation between air emissions embodied in import and consumption in these economic sectors, as presented in Fig. 8. Some economic sectors with large shares of air emissions embodied in imports compared to those of consumption include trade, pharmaceutical, computer and electronics, textile and leather, information and communication, transport equipment, and etc. For example, 63 % of CO_2 emission in 2017 of transport equipment sector originates from imported products.

It should be noted that the number of regions in this study is limited, including only two regions: Italy and RoW. While the number of regions has no impact on the PBA emissions because PBA is the direct emissions from production and consumption activities of the national economy, the number of regions is expected to cause potential impacts on CBA, due to the changes in emissions from import and export. In case Italy imported goods and service from countries with higher emission intensity than the average emission intensity of RoW, the emissions embodied in import will increase, compared to the obtained results of the existing model. Therefore, more detail of regions will bring a more accurate obtained results on emissions embodied in trade activities and CBA emissions.

During the 2017–2040 period, the shares of air emissions embodied in import out of consumption increases, for example, from 40.8 % to 49.5 % in CO_2 emission. These increases occur in all particular economic sectors. The largest CO_2 emission increases are among electricity, information and communication, and finance and insurance sectors, at around 11–12% points in the same period. This indicates that the trend of transferring the national air emissions to other countries will continue in the mid-term.

Five economic sectors' consumption with relatively high shares of embodied CO_2 emissions are wholesale and retail, healthcare, food and beverage, electricity and construction (refer back to Fig. 7). In 2017, wholesale and retail contribute to more than 12 % of the total CBA CO_2 emission of Italy. The four remaining sectors account for an average CBA CO_2 emission, from 6 % to 10 % of the total CO_2 emissions. By 2040, the shares of emissions of these sectors remain in the same range. This emission pattern suggests that between 2017 and 2040, in order to reduce the national CO_2 emissions, effort should be focused on these 'hotspot' sectors. Besides, the different contributions of domestic and import emissions to the total emissions suggest that Italy should have proper strategies to reduce its emissions in terms of geographical effort. CO_2 emissions of Italian trade partners for food and beverage, health, construction, and wholesale and retail should be taken into account because their emissions largely depend on imports (see Fig. 8). The effort should be taken either to reduce their trade partners' emission intensity, or to move away from trade partners that have high emission intensities. Meanwhile, equal effort should be shared between local manufacturers and trade partners being relevant to renewable power technologies such as solar, wind and other renewables.

3.5. Uncertainty analysis and sensitivity analysis

The uncertainty of the CO_2 emissions of the Italian electricity sector is analysed using Monte Carlo simulation for 1000 runs. In 2017, the production-based CO_2 emissions of the Italian electricity sector range from 95.19 to 99.54 $MtCO_2e$, with the mean value of 97.54 $MtCO_2e$, and standard deviation of 0.54 $MtCO_2e$. By 2040, these emissions range from 25.31 to 26.46 $MtCO_2e$, with the mean value of 25.92 $MtCO_2e$ and standard deviation of 0.17 $MtCO_2e$. The uncertainty analysis of PBA and CBA emissions of the Italian electricity sector in 2017 and by 2040 is presented in Fig. 9.

The sensitivity analysis is conducted with updated IOT and NAMEA for 2019. The purpose of this analysis is to observe any change in the model's results due to economic interactions without altering the technology's market share from 2017. A slight change is identified in the CO_2 emission of the Italian electricity sector from CBA perspective, while there is no change in the PBA emission, as presented in Fig. 10. Specifically, the CBA CO_2 emission of the Italian electricity sector reduces from 34.9 in 2017 to 34.3$MtCO_2e$ in 2019.

Moreover, the national CO_2 emission reduce in both PBA and CBA perspectives as presented in Fig. 11. The PBA national emission increases by 1 $MtCO_2e$ from 2017 to 2019, which indicates the increase in emissions of other economic sectors being connected to the electricity sector. In other words, if the electricity sector is not decarbonized, the CO_2 emissions will increase due to national production and consumption activities. In contrast, between 2017 and 2019, the CBA national emission decreases by 4 $MtCO_2e$, which originates from the trade activities between Italy and RoW.

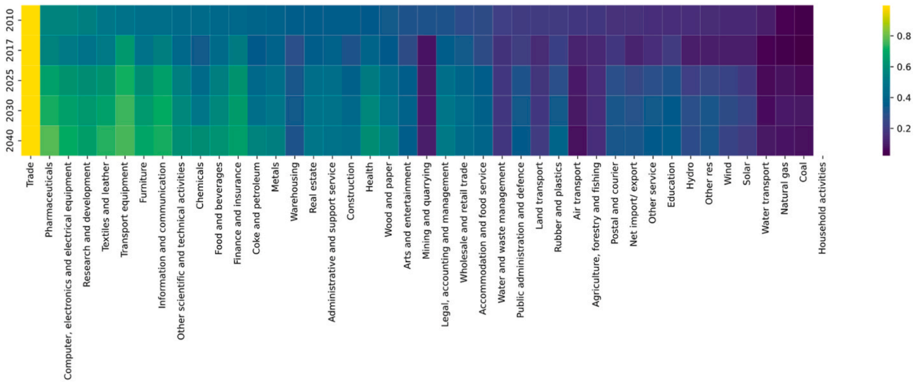


Fig. 8. Share of CO_2 emission embodied in imports, relative to consumption, by year.

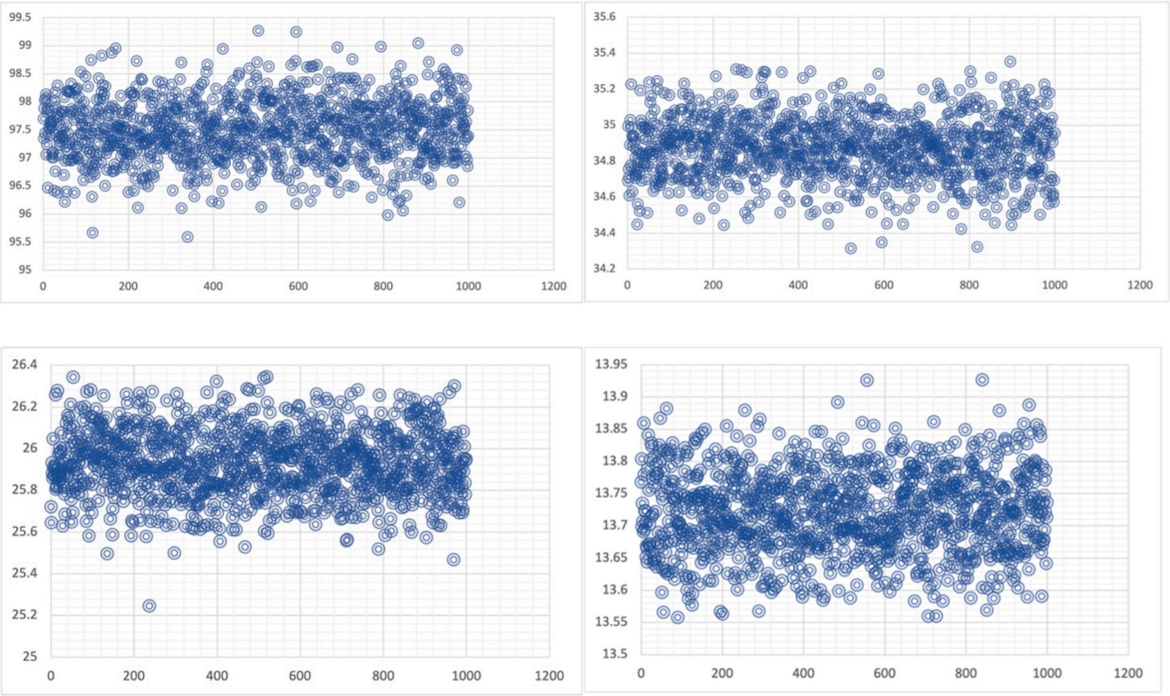


Fig. 9. Uncertainty analysis of CO2 emissions of Italian electricity sector in 2017 and by 2040. Top left: PBA 2017, top right: CBA 2017, bottom left: PBA 2040, bottom right: CBA 2040.

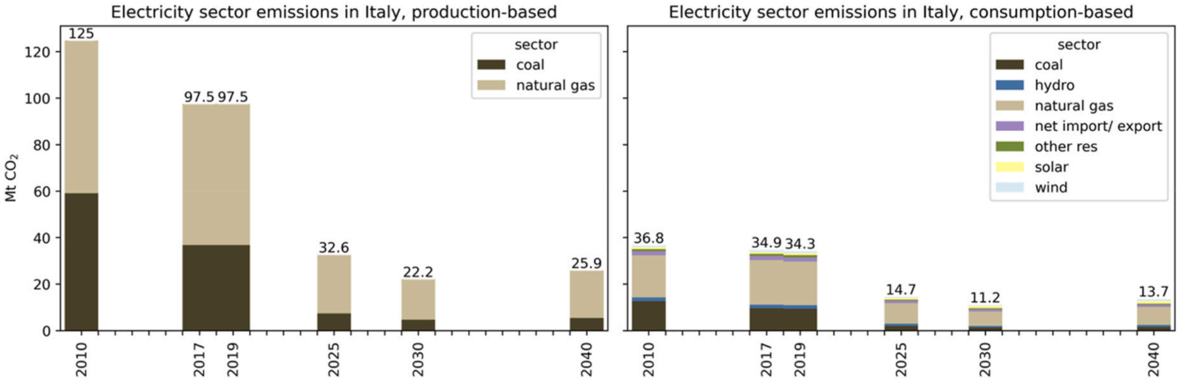


Fig. 10. Sensitivity analysis of CO_2 emission of Italian electricity sector.

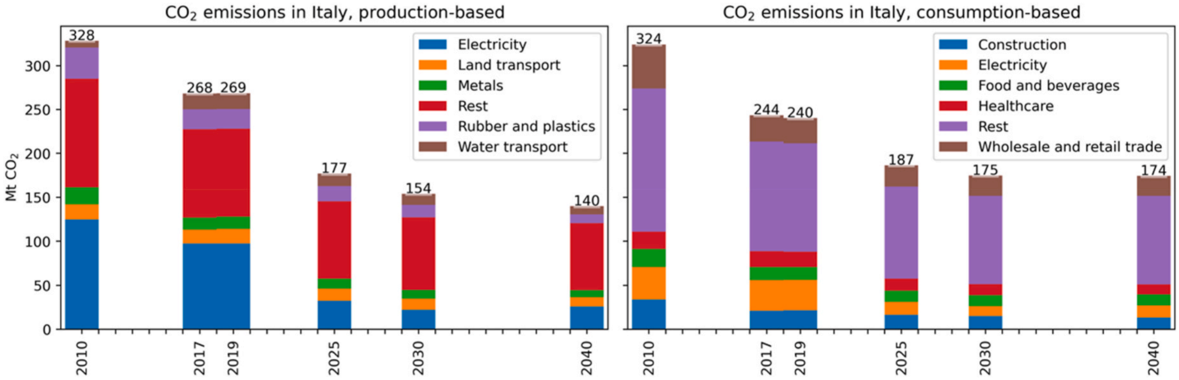


Fig. 11. Sensitivity analysis of CO_2 emission of national economy.

3.6. *Limitations of the H-MRIO approach*

Similar to IOA, H-MRIO is a static model. While time-differentiated factors have been integrated into the model (power development scenarios, change in final demand, and a forecast of emission volume of the future years), there are some limitations belonging to the 'static' characteristics of the model. First, the model is based on fixed price, meaning that there is no change in the price of products before and after the integration of power development scenarios, as well as between 2017 and 2040. Second, prices are the same for different power technologies. Though the purchase price of power is the same for all technologies, the production price should be different among electricity generation technologies.

Moreover, the hybridization is a time-consuming process. For the development of MRIO matrix, Istat and EXIOBASE data need to be matched. Economic sectors of these two databases are classified differently; and there is also a variation in the level of sectoral aggregation. For the hybridization of stressor matrices, the Ecoinvent and NAMEA data need to be matched. Again, the different granularity between two data sets requires time to match them, and in some cases, matching is simply not possible directly. It is suggested that in future studies, the level of aggregation should be more specified to reflect the diversity of technologies in the electricity, gas and steam sector.

The integration of future power development scenarios utilizes the similar and linear-forecasted intermediate flow matrix (for other economic sectors excluding the electricity sector). Though the future intermediate flow matrix may be similar to the current one in the short term, it is not convincing that in the long term, they will be similar. It is expected that with the increase in energy efficiency, material efficiency and sector productivity, there will be a lot of (non-linear) changes in the long term. Future studies should take into account these aspects when forecasting the future intermediate flow matrix.

Lastly, the study is restricted by data availability for power development scenarios. Considering that recent EU policy such as the "Fit for 55" package is internalized into national policy, in which the new Emission Trading System that will be applied to private transportation and buildings, there will be a change in the electricity sector, as well as other energy-intensive industries such as transportation and buildings. At the same time, the further requirement of climate targets will initiate more diverse low-carbon energy technologies to include battery energy storage systems and hydrogen; as well as emission reduction options related to social behaviour change. In that context, a comprehensive (and updated) energy transition scenarios should be developed, and extended from the electricity sector to economic-wide sectors.

4. Conclusion and prospects

In the context of climate risk with multiple proposals for decarbonizing the energy sector, this paper introduced a H-MRIO model with integration of energy development scenarios for quantifying the sectoral and national air emissions. The method extends the quantification boundary beyond the energy sector to include other economic sectors within the energy supply chain. Some of these economic sectors are more affected by the decarbonization of the energy sector, while others bear fewer impacts. Additionally, the method highlights the relationship between emissions embodied in trade activities, i.e. import and export, and decarbonization of the energy sector.

The quantification results on the life cycle air emissions of the Italian electricity sector and national emissions from PBA and CBA perspectives showed that during 2010–2040, the electricity sector's air emissions drop significantly due to changes in economic structure, emissions intensity and the decarbonization of the electricity sector itself. Moreover, Italian air emissions are roughly halved, a trend that occurs in most economic sectors. The forecasted energy transition not only shrinks emissions in the electricity or energy sector, but reductions spread to other economic sectors along the energy supply chain. The study points out the important contribution of imports in national air emissions. Trade, pharmaceutical, computer and electronics, textile and leather, information and communication, and transport equipment, are particularly high importers of embodied carbon. This illustrates the limits of energy scenarios at the national scale, and supports the need for international policy measures.

The method and the practical application of the model show their advantages in evaluating scenarios for the introduction and massive deployment of RES in reducing GHG emissions in the energy sectors and relevant economic sectors during the energy supply chain. However, there are scientific gaps which should be addressed in the near future, such as developing the method for integrating the changes in energy efficiency, material efficiency and sector productivity into the quantification process. Another area for future research is to extend the analysis to various environmental impacts such as material consumption, and sustainability impacts, as mentioned in Ref. [44] which are very important in the current material shortage and sustainable development context.

Credit author statement

Le Quyen Luu: Conceptualization, Methodology, Resources, Data curation, Writing – original draft, Writing – review & editing. **Thomas Gibon**: Conceptualization, Methodology, Resources, Data curation, Writing – original draft, Writing – review & editing, Supervision. **Maurizio Cellura**: Conceptualization, Resources, Writing – original draft, Writing – review & editing, Supervision. **Eleonora Riva Sanseverino**: Resources, Data curation, Writing – original draft, Writing – review & editing, Supervision. **Sonia Longo**: Methodology, Resources, Writing – original draft, Writing – review & editing. All authors equally contributed to the paper's development and writing. All authors have read and agreed to the published version of the manuscript

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Le Quyen Luu, Maurizio Cellura, Eleonora Riva Sanseverino reports financial support was provided by European Union. Thomas Gibon reports a relationship with FNR project that includes: funding grants.

Data availability

I have shared the link for the data and codes in the manuscript.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2023.130109.

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