Università
degli Studi
di Palermo

AREA QUALITÀ, PROGRAMMAZIONE E SUPPORTO STRATEGICO
SETTORE STRATEGIA PER LA RICERCA
U. O. DOTTORATI

Dottorato di Ricerca in Energia e Tecnologie dell'Informazione
Dipartimento di Ingegneria

CONSEQUENTIAL LIFE CYCLE ASSESSMENT OF THE ITALIAN POWER SYSTEM

IL DOTTORE
LE QUYEN LUU

IL COORDINATORE
PROF. MAURIZIO CELLURA

IL TUTOR
PROF. MAURIZIO CELLURA

EVENTUALE CO TUTOR
PROF. ELEONORA RIVA SANSEVERINO

CICLO XXXV
2022

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ABSTRACT

Energy production and consumption contribute to 76% of the European greenhouse gas (GHG) emissions in 2018, and 90% of global GHG emissions with land use, land use change and forestation (LULUCF) in the same year. By applying energy efficiency (EE) and renewable energy (RE) technologies, the GHG emission intensity of the energy sector reduced by 1.3% in 2018 compared to the previous year.

The current climate change policy aims at decarbonization, sustainable environment, economic prosperity and social equity. It requires the deep decarbonisation of the economies, meaning that the energy and power systems as well as other emission intensive sectors need to transform into zero-emission ones. It also requires the minimization of the environmental impacts while ensuring the economic development and meeting the need of the population growth.

This thesis quantifies and evaluates the life cycle environmental impacts with focus on GHG emissions of the power sector, as consequences of changes in the environmental policy. Specifically, the thesis will answer five research questions:

1. What are climate change and energy/ power development policies in Italy?
2. What are changes in the energy/ power systems as consequences of energy climate policies?
3. What are the methods and approach for quantifying and evaluating life cycle environmental impacts as consequences of changes?
4. What are the life cycle environmental impacts of the Italian energy/ power system, with focus on GHG emissions, as consequences of changes in environmental and power policies?
5. The interactions between the energy climate policies and the environmental impacts/ GHG emissions of the Italian power system?

The thesis is structured into six chapters, including two chapters of introduction and conclusion, and four chapters of answering five above-mentioned research questions. Chapter 2 provides the answers for two questions (Question 1 and Question 2) on climate and energy policies and changes in the Italian energy/power system due to climate and energy policies.

Climate change and energy/ power development policy in Italy is presented in five main documents: FIT for 55, Integrated national energy and climate plan (NECP), national energy strategy (SEN), national energy efficiency action plan (PAEE), and national renewable energy action plan (NREAP). The four national documents set out the targets for EE and RE. Specifically, the targets of energy savings by 2030 include 43% reduction in primary energy consumption, 0.8% reduction in annually final energy consumption without transportation sector and 10 MTOE final energy consumption reduction. For RE, by 2030, the target is 28% ~

30% of share of RE in total energy consumption, 55% of RE share in electricity consumption and 21% ~ 22% of RE share in transportation sector.

It is expected that the electricity generation technology mix will change in order to meet the requirement on RE and EE targets set out in the Italian energy and climate policies. In this thesis, the energy scenarios called National Trend Italia (NT Italia) will be used. The NT Italia was developed by Terna and Snam, for the horizon years 2025, 2030 and 2040, using modelling tools for electricity demand, gas demand and market simulation. In these scenarios, the installed capacity of electricity by natural gas, which is slightly increased by 2040. The installed capacity of coal-based electricity and other fossil fuels-based electricity reduce from 7GW currently to 2GW by 2025, and will not change then. The scenarios also see a constant growth of electricity by RE, reaching 64 GW for solar and 25 GW for wind power (including 4.2 GW offshore) by 2040, while the installed capacity of hydropower and other renewable electricity will be stable.

Chapter 3 and Chapter 4 of this thesis will deal with the research question 3, in which Chapter 3 is about the methodology and Chapter 4 focuses on the applied framework. In Chapter 3, the state of the art of consequential life cycle assessment (C-LCA) in the energy and power sectors has been reviewed. The review was conducted on 43 case studies of C-LCA in energy sector and 31 C-LCA papers in power sector. It was identified that economic models are frequently applied in combination with life cycle assessment (LCA) to conduct a C-LCA study in energy and power sectors. The identified economic models include equilibrium (partial and general equilibrium), input-output, and dynamic (agent based and system dynamic) models. Out of these, the equilibrium model is the most widely used, showing some strengths in availability of data and energy system modelling tools. The input-output model allows for describing both direct and indirect effects due to changes in the energy sector, by using publicly available data. The dynamic model is less frequently applied due to its limitation in availability of data and modelling tools, but has recently attracted more attention due to the ability in modelling quantitative and qualitative indicators of sustainability. The review indicates that the most suitable approach to conduct the study is combining one or several economic models and LCA to assess the consequential life cycle impacts of the power system. As each economic model has their own strengths and limitations, the choice of the applied models in combination with LCA largely depends on the goal of the study, the nature of the changes due to market mechanisms, economic or social origins, and the availability of data.

In Chapter 4, a framework of combining Input Output Analysis (IOA) and process-based LCA for conducting the study was proposed. Moreover, this chapter provides detailed information on data collected for the model. There are several weighting points for proposing this framework. Firstly, the goal of the study is to assessing the consequential life cycle impacts of energy/ power systems. It requires the comprehensive overview of all economic sectors, as energy is connected all economic activities. The comprehensiveness will be ensured by applying IOA. At the same time, the process-based LCA will provide the detail of a sector/ a product system, which is normally a limitation of economic-wide tool such as IOA. Secondly, the change in the power system originates from economic activities (supply and demand of energy) as well as the environmental requirement to GHG emission reduction and zero carbon emissions. This change can be well modelled with an economic analysis tool (IOA) in combination with an environmental management tool (processed-based LCA). Finally, data for these tools is publicly available. The IOA depends on the input output tables (IOT), which is published every five years by the Italian Statistics (Istat). Data on energy sector is collected from Energy Balance Table, published annually by Ministry of Economic Development, the data from Terna and Snam, the database of the International Energy Agency (IEA), International Renewable Energy Agency (IRENA) and European Commission. Data on environmental aspects includes the National Accounting Matrix with Environmental Accounts (NAMEA), being collected from Istat. Data for process-based LCA is taken from ecoInvent 3. Some global database for IOA are available such as World Input Output Database (WIOD), EXIOBASE, and ect.

Followings is the general framework for combining IOA and processed-based LCA to conduct a C-LCA. Consequential life cycle impact is the subtraction of the life cycle impact 'after change' and the life cycle impact 'before change'. The life cycle impact 'before change' is quantified by applying IOA. The life cycle impact 'after change' depends on the change of pollutant amount, technological coefficient and the final demand due to the inclusion of renewable energy into the Italian energy system. In this thesis, multiregional input output (MRIO), a variant of IOA is used to cover several regions or countries. The application of hybrid MRIO and process-based LCA (hereinafter being called as H-MRIO) is described as followings:

- First, two types of data, including MRIO and hybridization data are collected. MRIO data such as the Italian and multiregional IOTs and air emissions accounts are collected from Istat and EXIOBASE. Hybridization data is collected from Italian power/energy suppliers for power development scenarios, and from the ecoinvent database for direct air emissions of power generation technologies
- From MRIO data, the MRIO model with two regions of Italy and Rest of the World (RoW) and 36 economic sectors will be constructed.
- In combination with the power development scenarios, the Italian electricity sector is disaggregated into seven power generation technologies, for both intermediate flow matrices and final demand vectors in Italian IOT. Similarly, in the environmental burden matrices, the air emissions of electricity sector are disaggregated into those of seven power generation technologies, with data taken from ecoinvent. At this time, the H-MRIO model composes of 42 sectors (36 economic sectors - 1 electricity sector + 7 power technologies).
- The model is calculated with historical data of 2010 and 2017 (reference scenario) and replicated for the future scenarios of 2025, 2030 and 2040.

Chapter 5 focuses on applying the proposed H-MRIO framework on the Italian context, to obtained the answers for the last two research questions (Question 4 and 5). The total GHG emissions to meet global final demand in 2017 calculated in the study is at 47.69 $GtCO_2e$, which is slightly higher than the global GHG emissions estimated by Climate Watch, at 47 $GtCO_2e$ excluding Land use change and forestation (LUCF). The difference in the obtained results of this model and other models is caused by the difference in scope of air emissions being studied. This model quantified actual anthropogenic emissions of CO_2, CH_4 and N_2O, excluding emissions from LULUCF 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 LUCF. This causes a difference of around 1 $GtCO_2eq$ of F-gases and 2.8 Gt CO_2eq of CH_4. The exclusions 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%).

In order to look into details of the sources of the change in the air emission, a decomposition analysis has been conducted. With the change in final demand and electricity sector composition of Italy, consumption-based GHG emissions appear to decrease in the period 2010-2040. Specifically, due to changes in production structure, emission coefficients, and final demand, the annual CO2 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 $MtCO_2$. While the change in production structure, including 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.

Due to the change in power supply technologies and power consumption, the future air emissions dramatically reduce in electricity sector. Most of the emissions of the domestic electricity production come from fossil fuel based electricity, e.g. electricity by coal and natural gas. A smaller part comes from other renewable electricity, including geothermal and biomass based electricity. The productions of solar and wind power do not generate any air-borne emission, and that of hydropower emits an amount of N_2O. The reduction in electricity from fossil fuels such as coal and natural gas help to reduce the emissions of the domestic electricity production nearly four times from 97.5 $MtCO_2$ in 2017 to 25.9 $MtCO_2$ by 2040. Besides, the CO_2 emission of final consumption of electricity is 34.9 $MtCO_2$ in 2017, which reduces by more than half, at 13.7 $MtCO_2$ by 2040. The CO_2 emission of final electricity consumption 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 emissions of final electricity consumption are smaller than that of domestic electricity production, as they are shared by other economic sectors as intermediates for production activities.

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 increase or decrease 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 percent point). Meanwhile, the

CO_2 emission shares of some sectors increases, such as food and beverage (increasing less than 1 percent point). It should be noted that the CO_2 emission contributions of these sectors to the national final consumption 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 $MtCO_2$ annually; or healthcare, decreasing from 17.7 $MtCO_2$ to 11.43 $MtCO_2$ or 0.27 $MtCO_2$ annually in the same period.

Five economic sectors holding larges shares out of total CO_2 emission of final consumption includes: wholesale and retail, healthcare, food and beverage, electricity and construction ('hotspot' sectors). In 2017, wholesale and retail contribute to more than 12% of the total CO_2 emission of the Italian final consumption. The four remaining sectors account for an average 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 term 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 depends on import. The effort should be taken either to reduce their trade partners' emission intensity, or to move away from trade partners that having 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 renewable.

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ABBREVIATIONS

ABM	Agent Based Modelling
AEA	Air Emissions Account
ALCA	Attributional life cycle assessment
BAU	Business as usual
C-LCA	Consequential life cycle assessment
CBA	Consumption-based accounting
CCS	Carbon capture and storage
CFC	Chlorofluorocarbon
CH_4	Methane
CHP	Cogeneration of electricity and heat
CLRTAP	Convention on Long Range Transboundary Air Pollutants
CO	Carbon monoxide
CO_2	Carbon dioxide
CSP	Concentrating solar power
DM	Dynamic model
DSO	Distribution System Operator
EC	European Commission
EE	Energy efficiency
EGSS	Environmental Goods and Services Sector accounts
ELE	Only electricity generation
EPEA	Environmental Protection Expenditure Account
ETS	Emissions Trading Scheme
EU	European
Eur	Euro (currency)
EV	Electric vehicle
EW-MFA	Economy Wide Material Flow Account
FPMF	Fine particulate matter formation
gCO_2e	Gram of carbon dioxide equivalent
GDP	Gross domestic product
GE	General Equilibrium
GHG	Greenhouse gas
$GtCO_2e$	Giga tonne of carbon dioxide equivalent
GW	Gigawatt
GWP	Global warming potential
HFC	Hydrofluorocarbon
HT	Human toxicity
I&C	Information and communication
IEA	International Energy Agency
IO	Input-Output
IPCC	Intergovernmental Panel on Climate Change

IRENA	International renewable energy agency
$kgCO_2e$	Kilogram of carbon dioxide equivalent
km	Kilometer
kt	Thousand tonne
LCA	Life cycle assessment
LCIA	Life cycle impact assessment
LCOE	Levelized cost of electricity
LULUCF	Land use, land use change and forestation
m^3	Cubic meter
Mt	Million tonne
$MtCO_2e$	Million tonne of carbon dioxide equivalent
MTOE	Million tonne of oil equivalent
MW	Megawatt
MWh	Megawatt hour
N_2O	Nitrous oxide
NACE	Nomenclature of Economic Activities
NAMEA-Air	National Accounting Matrix with Environmental Accounts Air Emissions
NEA	Nuclear Energy Agency
NECP	Integrated National Energy and Climate Plan
NH_3	Ammonia
NMVOC	Non-methane volatile organic compound
NOx	Nitrogen oxides
NREAP	National Renewable Energy Action Plan
NT Italia	National Trends Italia
O&M	Operation and maintenance
ODP	Stratospheric ozone depletion
OECD	Organisation for Economic Co-operation and Development
OFP, HH	Ozone formation (Human health)
OFP, TES	Ozone formation (Terrestrial ecosystems)
PAEE	Energy Efficiency National Action Plan
PBA	Production-based accounting
PCOP	Photochemical oxidation
PEFA	Physical Energy Flow Account
PEM	Partial equilibrium model
PEP	Primary energy Production
PFC	Perfluorinated compound
PM_{10}	Particulate matter less than 10 micrometer
$PM_{2.5}$	Particulate matter less than 2.5 micrometer
RE	Renewable energy
RES	Renewable energy sources
SD	System Dynamics

SEN	National Energy Strategy
SF_6	Sulphur Hexafluoride
SME	Small and medium-sized enterprise
SNA	System of national accounts
Solar PV	Solar photovoltaics
SOx,	Sulphur oxides
TES	Total energy supply
TFEC	Total final energy consumption
TSO	Transmission System Operator
TWh	Terawatt hour
UK	The United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change
US	The United States of America
USD	The United States Dollar (currency)
V2G	Vehicle to Grid
WB	World Bank

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CHAPTER 1. INTRODUCTION

This chapter will describe the global and Italian scenarios for the considered research problem, outline the motivation for conducting the research, and contribution of the research. It also provides the research questions and describes the specific objectives of the research (presenting in forms of sub-research questions). Finally, this chapter will set the outline of the thesis.

The study covers the time frames of 2017 – 2040. The year 2017 is used as the reference year, and several time intervals of 2017-2025, 2017-2030 as well as 2017-2040 will be considered. Moreover, some calculations for the historical year 2010 have been referred to observe the change in different periods.

1.1. Power systems' development, GHG emissions of power systems and climate change policies

Greenhouse gas (GHG) emissions of the energy sector are considered as a hot spot at national and global scales due to their large share of the total emissions. According to the European Environment Agency, energy production and consumption contributed to 76% of the EU-28 and Iceland's GHG emissions (EEA, 2018).

By 2018, the greenhouse gas (GHG) emissions with land use, land use change and forestation (LULUCF) of Annex I countries was 14.91 $GtCO_2e$ (UNFCCC, 2020). The emissions of the energy sector accounted for 90% of the total emissions (13.47 $GtCO_2e$) (UNFCCC, 2020). The power and heat generation sectors, in particular, contributed to 9.76 $GtCO_2e$ in 2017 and increased by 2.5% in 2018 (IEA, 2020a). Although there was a small reduction in emission intensity of 1.3% as a result of the application of renewable energy and energy efficiency technologies, the growing demand for electrical power is the principal cause of the increase in total GHG emissions.

The trend of current GHG policies aims at decarbonization, sustainability, economic prosperity, and social equity (Carnevale and Mattei, 2020). It requires the deep decarbonization of the economies, in which the energy systems as well as other emission-intensive sectors need to transform into zero-emission ones while ensuring economic development and meeting the needs of a growing population (DDPP, 2015). The Deep Decarbonisation Pathway Project countries, which contribute to 74% of global energy-related GHG emissions, set the objective that by 2050 their GHG emissions of the energy sector will be reduced by 46-56% as compared to the 2010 level while maintaining the average gross domestic product (GDP) growth of 3.1% and the population growth of 17% annually (DDPP, 2015).

However, during the decarbonization process, there are trade-offs on other environmental impacts and other economic sectors. In the power sector, for example, biomass-based electricity is believed to cause less GHG emissions as compared to coal thermal power, but it may increase eutrophication and acidification due to the energy crop plantation (Luu and Halog, 2016). In such cases, the GHG emissions of the power sector will reduce, but other negative environmental impacts from the agriculture sector will increase. Due to the link between the power sector and other economic sectors, any increase in power demand for different economic sectors will induce changes in the energy sector and its GHG emissions, and vice versa.

1.2. Italian context and research motivation

In order to cope with the GHG emissions, the European Commission (EU) has updated the Green Deal Package "Fit for 55"[1]. The package targets at reducing GHG emissions, including removal, by 2030 to at least 55% as compared to the 1990 level, aiming at carbon neutrality by 2050. The specific actions to meet the targeted emissions reduction relate to the reduction of primary energy, the increase of the renewable energy share, the inclusion of land transport and buildings into the Emission Trading Scheme (ETS), the reduction of GHG in the transport sector, the application of a carbon tax on import of cement, iron, aluminium, fertilizer and electricity not meeting the standard, the tax on energy production, some actions related to LULUCF and the effort sharing mechanism for sectors not covered by ETS.

The Italian climate policy aligns with the common EU policy[2], in which the national policy focuses on energy-related sectors, with the integration of climate and energy policies into one coherent document. The climate and energy policies set out the specific targets for GHG emission reduction, including a reduction in primary energy consumption and final energy consumption, an increase in the share of gross final energy consumption from renewable sources and the share of renewables in the transportation sector.

Specifically, by 2030, the Italian targets are a 43% reduction in primary energy consumption, a 39.7% reduction in final energy consumption (or a 0.8% reduction per year) taking into account the transportation sector, compared to the PRIMES 2007 scenario, 30% of gross final consumption of energy coming from renewable sources

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[1] https://italyforclimate.org/stakeholder-forum-sul-clima-di-i4c-il-nuovo-pacchetto-ue-di-proposte-fit-for-55/

[2] Although the newest EU policy – Fit for 55 has not localized into the national energy policy. Fit for 55 proposed to raise the energy saving in final consumption by 40% and renewable energy share by 50%.

and 10% of RE in the transportation sector by 2030[3] (Ministry of Economic Development, 2017a; MISE et al., 2019).

In order to meet the binding commitment to GHG emission reduction, a mixture of actions is needed in all economic sectors. The integration of RE and EE, and the interaction of these measures with the socio-economic sector will not only impact the technical aspects of the energy sector, but also change its economic and environmental profile and the wider economic perspective. This study will assess the environmental impact, with a focus on GHG emissions of RE and EE by 2040. The consequential life cycle assessment (C-LCA) will be applied to provide a comprehensive view of the energy and GHG emission impacts of RE and EE. It is expected that the study results will partly support decision-makers in optimizing the system in relation to economic cost and environmental benefits.

1.3. Contribution of the study

A literature search which was conducted at the beginning of 2020 on C-LCA in the energy sector, indicated that the concept of C-CLA has been agreed on, while it is not clear how to conduct a C-LCA. There are several approaches of combining economic modelling and LCA for conducting a CLA. These approaches will be further explained in the following chapters. The literature search also reported that the number of C-LCA in the power sector was limited, at 31 papers out of 102 case studies identified during the literature search, though the power sector is the input provider for most of other economic sector and plays an important role during the supply chains of different products.

This study will contribute to the scientific area of C-LCA in the power sector in terms of research methodology and obtained results. In term of methodology, this study will examine the combination of economic modelling, specifically input output analysis and LCA for quantify life cycle environmental impacts of the power system. Moreover, the obtained results of the study do not only limit in the life cycle environmental impacts of the power system, but also explore the spill-over effects of decarbonizing the power sectors on other sectors and other regions.

1.4. Research questions

This thesis aims at quantifying and evaluating the life cycle environmental impacts, with a focus on GHG emissions of the energy/ power sector, as a consequence of

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[3] NECP 2019 and SEN 2017

changes in environmental and power-related policies. Specifically, the research question is the following:

What are the life cycle environmental impacts (GHG emissions) of the Italian power system (including on-grid renewables and energy efficiency development) considering the policies on power development and climate change mitigation?

Specific sub-research questions:

- What are the climate change and energy/power development policies in Italy?
- What are the changes in the energy/ power system as consequences of the energy and climate policies?
- What are the methods and approaches for quantifying and evaluating life cycle environmental impacts as consequences of changes?
- What are the life cycle environmental impacts of the Italian energy/ power system, with a focus on GHG emissions, as consequences of changes in the environmental and power policies?
- What are the interactions between the energy climate policy and the environmental impacts/ GHG emissions of the Italian power system?

1.5. Research outline

This thesis is structured in the same sequence of the five above-mentioned research questions. Each following chapter will answer each research question. The next chapter will answer the first and second questions. It will thus describe the climate change and energy power development policies in Italy, and analyse the changes in the Italian future energy/power system as consequences of energy and climate policies.

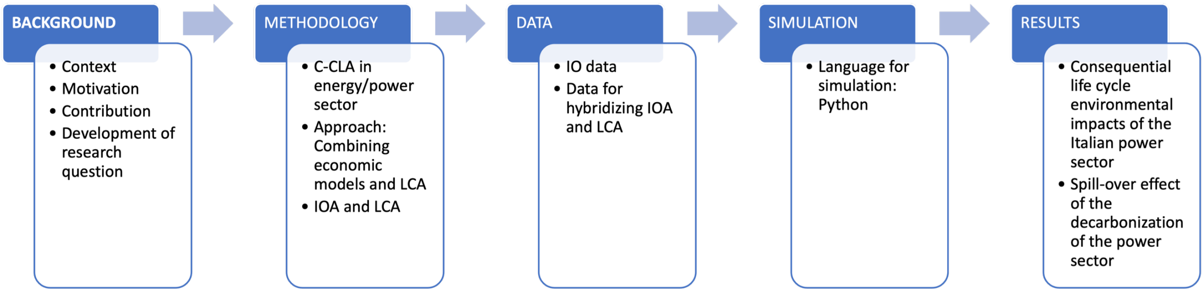
Subsequently, the literature review of the state of the art of C-LCA in the power sector is presented as well as the justification for the selected approach and the proposed methodological framework for conducting a C-LCA on the Italian energy/power sector. The methodology and framework will be presented in two subsequent chapters, one focusing on the methodology of C-LCA, while the other concentrating on an applicable and specific framework for conducting the study. In the following chapter, a description of the collected data is included. This will be the answer to the third research question.

The thesis will conclude with the last chapter answering questions 4 and 5. This chapter presents the results of the study, including the life cycle environmental impacts of the Italian energy/power system, with a focus on GHG emissions, as consequences of changes in environmental and power policies. Then the interactions between the energy climate policy and the environmental impacts/GHG emissions of the Italian power system and other economic sectors are reviewed and commented.

Besides, a sensitivity analysis is conducted to compare the different modelling methods. Finally, a discussion of the obtained results and chosen method, and suggestions on future applications for research are outlined.

The Figure 1 present the research framework, clarifying different steps and relevant mains activities of the study.

Figure 1 . Research framework



BACKGROUND

- Context
- Motivation
- Contribution
- Development of research question

METHODOLOGY

- C-CLA in energy/power sector
- Approach: Combining economic models and LCA
- IOA and LCA

DATA

- IO data
- Data for hybridizing IOA and LCA

SIMULATION

- Language for simulation: Python

RESULTS

- Consequential life cycle environmental impacts of the Italian power sector
- Spill-over effect of the decarbonization of the power sector

CHAPTER 2. ENERGY CLIMATE POLICY AND ITALIAN ENERGY SECTOR

This chapter describes the Italian energy sector, providing background information on the country's economic profile. The national energy sector is presented in four key points, including supply, demand, cost and policy. At the end of the chapter, the national energy development scenarios are reported.

2.1. Country profile

Italy is a mountainous country, running from the Alps to the central Mediterranean Sea, with two large islands and about 70 small islands. The total area is 301,300 km^2; half of which is arable land. The national population amounts to 61.6 million, a third of which is actively employed. The official language is Italian; however, in some regions, other languages such as German, French and Slovenian are also used.

Italy is a republic, with a bicameral national legislature, the senate and the chamber of deputies. The council of ministries, headed by the Prime Minister, is appointed by the President. The President is elected by the electoral college of the senate, the chamber of the deputy and the representatives of regions. The President's term lasts 7 years, and he/she has no executive powers.

Italy is divided into 20 regions, including 4 autonomous regions and 2 autonomous provinces. The regions have their own legislative and regulatory powers. In 2001, the framework to share regulatory competencies between the state and regions has been introduced, including a framework for energy regulatory competence.

Before 2017, the Italian economy is struggling to emerge from a prolonged recession caused by fiscal austerity, weak business and consumer confidence, deteriorating labour market conditions, modest wage growth and tight credit conditions (EIU, 2015). Since 2020, the early onset of covid-19 in Italy and the war in Ukraine have severely impacted the national economy. The intensive lockdown and the change in working modes which were necessary for isolating covid-19 limited economic activities (OECD, 2021). After that, the war in Ukraine caused an increases in energy, agricultural and metal prices, as Russian, Ukraine and Belarus are the main providers of these products (Fontana, 2022). Although there was a rebound in economic growth after the covid-19, the war has slowed down the growth. In such context, the government policies is deemed to focus on higher growth and better energy price support for the vulnerable (OECD, 2022).

2.2. Supply and demand[4]

2.2.1. *Energy supply*

In 2017, the total energy supply (TES)[5] of Italy was 156 MTOE. Fossil fuels accounted for about 79.5% of the TES, in which natural gas had the highest share (at 39.4% or 61.5 MTOE), followed by oil and petroleum products (at 33.3% or 52 MTOE). The share of solid fuels accounted for a small percentage of 5.9%. Renewable Energy (RE) Supply mainly came from primary solid biofuels, geothermal and hydro. The total share of renewables, biofuels and waste contributed 19.2% of the TES. Those of geothermal and hydro were 3.5% and 1.9%, respectively. The shares of wind and solar energy were small, accounting for 0.9% and 1.5% of the TES. Figure 2 presents the share of RE supply from 2007 to 2017.

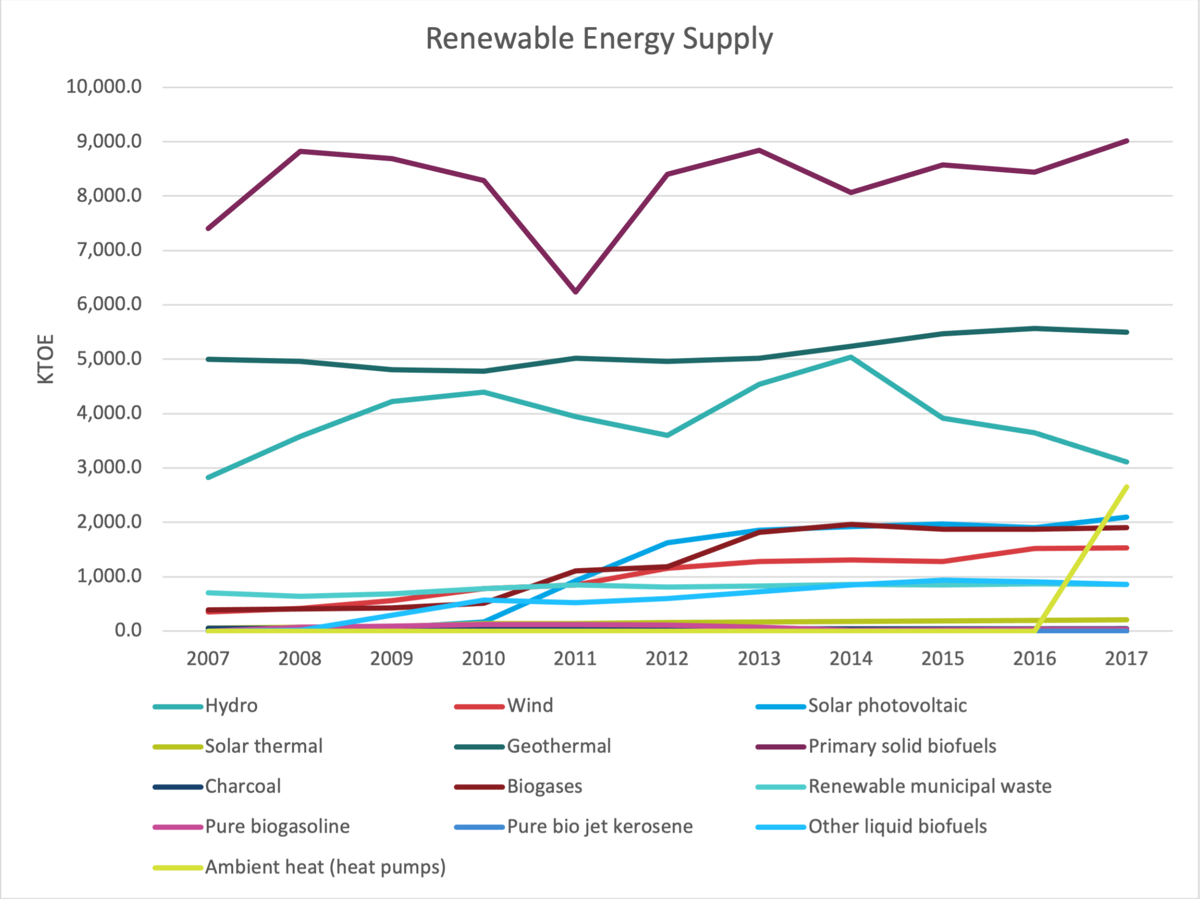


Figure 2 . Renewable energy supply between 2007 and 2017

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[4] This data analysis is based on Italian Energy Balance Table, being downloaded from the website of Ministry of Economic Development of Italy (https://dgsaie.mise.gov.it/bilancio-energetico-nazionale).

[5] TES = production + imp - exp +/– change in stock – international aviation – international marine = domestic consumption = transformation + final use

During this 10-years period, from 2007 to 2017, the TES decreased by 18%, being equivalent to 28.1 MTOE. Although there was a slight increase in 2008, 2010 and 2015, compared to previous years, the general trend is a gradual reduction. This trend was similar for all types of energy, except for renewables and biofuels, which rose at 7% annually (See Figure 3).

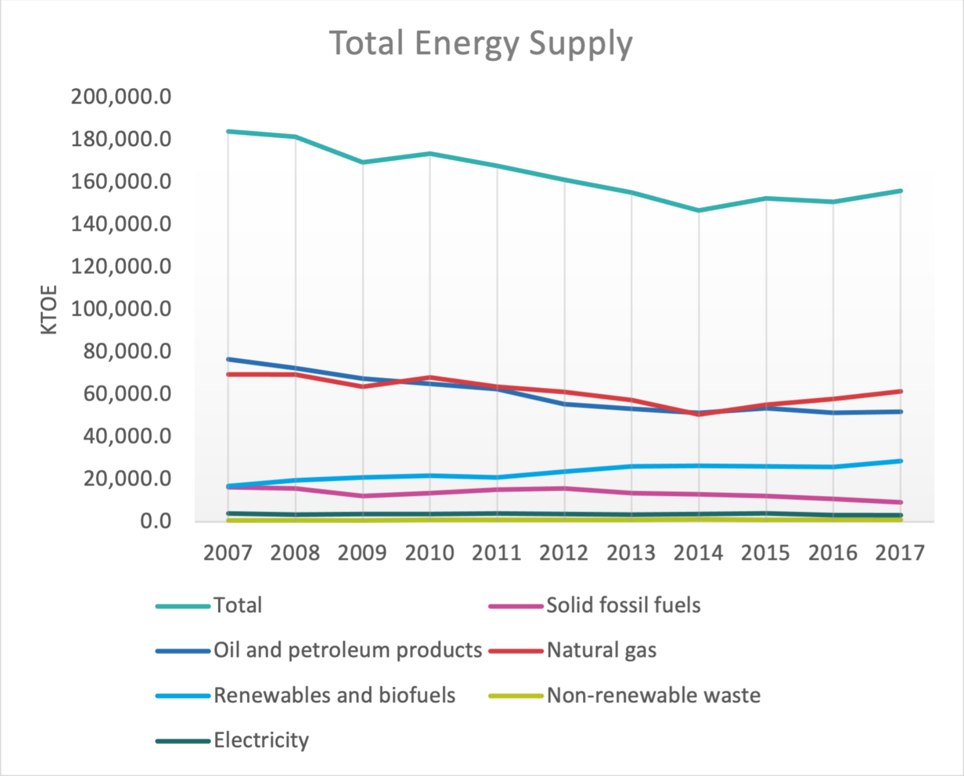

Figure 3. Total energy supply between 2007 and 2017

The Primary Energy Production (PEP) in 2017 is 36.6 MTOE. Between 2007 and 2017, the PEP tended to increase at 1.78% annually. Figure 4 presents the trend of PEP during the period 2007- 2017.

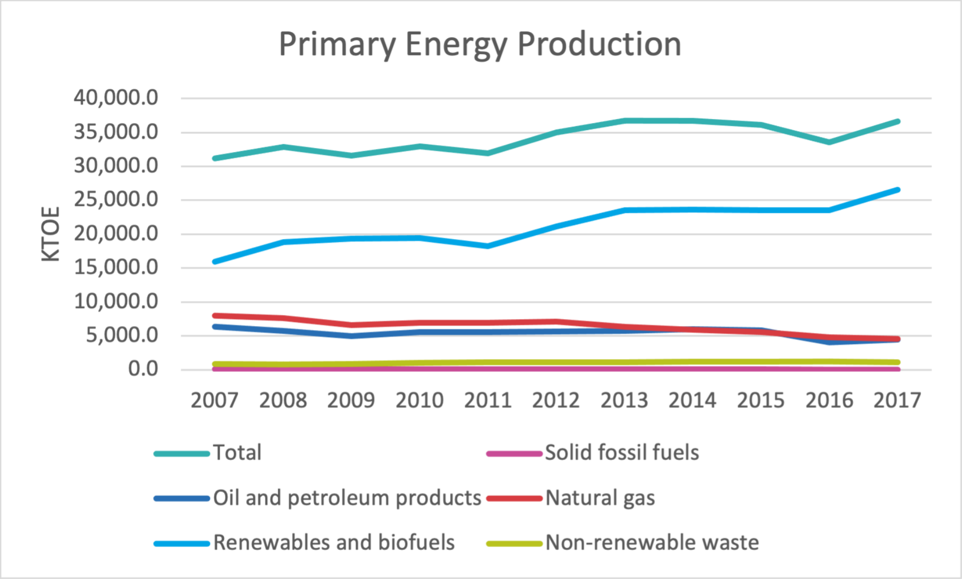

Figure 4 . Primary energy production between 2007 and 2017

The share of renewable accounted for more than half of the PEP, at 68.2% on average from 2007 to 2017, which mainly constituted primary solid biofuels (22.9%), geothermal (16.6%) and hydro (12.6%). The share of renewable tended to increase during the period 2007- 2017 reaching 26.5 MTOE, and it played an increasingly important contribution to the PEP from 51.2% in 2007 to 72.4% in 2017.

Shares of fossil fuels in the PEP were small, with respective percentages of petroleum and oil products, and natural gas of 12.1% and 12.4% in 2017. Shares of fossil fuels and renewables out of PEP in 2017 are presented in Figure 5.

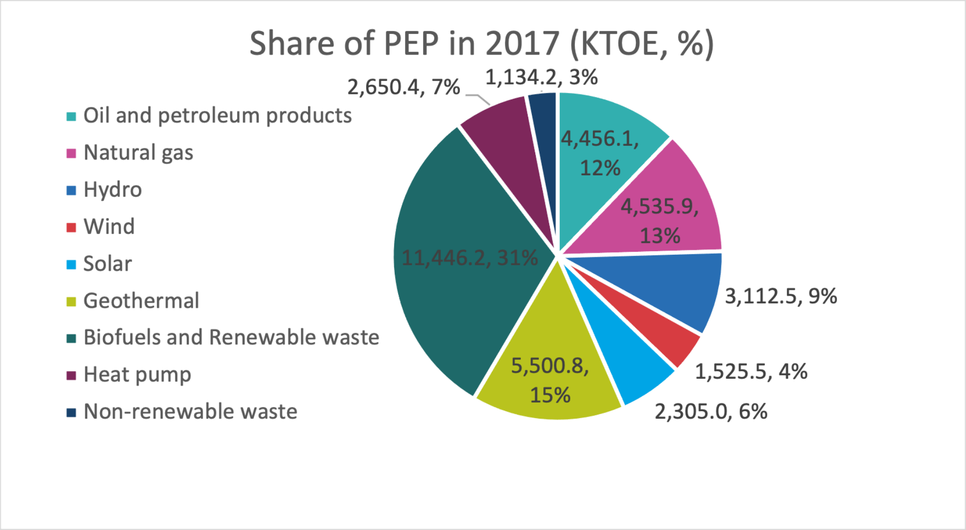

Figure 5 . Share of primary energy production in 2017

2.2.2. Energy demand

The total final energy consumption (TFEC) in 2017 was 113.6 MTOE, accounting for 61.7% of TES. The remaining of the TES was consumed in power generation and other energy industries. From 2007 to 2017, the TFEC slightly fluctuated and hit rock bottom in 2014 (108.8 MTOE) due to the decrease in natural gas consumption. In general terms, the TFEC decreased by 1.4% annually. This decreasing trend mainly originated from the decline in oil and petroleum product consumption, at 42.4%, from 54.5 MTOE in 2007 to 38.3 MTOE in 2017. The consumption of other types of energy including natural gas and electricity, which held large shares of the TFEC, slightly reduced, 6.8% and 5.9% respectively. Shares among types of energy in the TFEC are presented in Figure 6.

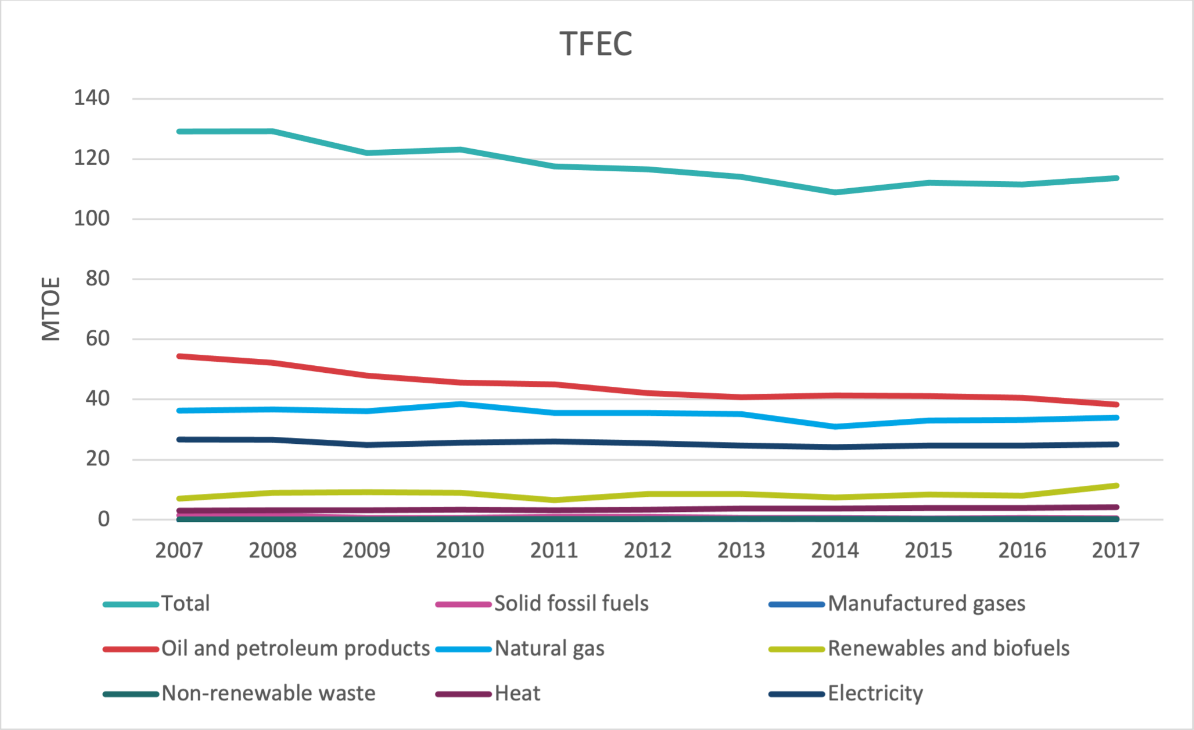

Figure 6. Total final energy consumption between 2007 and 2017

By sectors, in 2017 the TFEC is highest in the transport sector at 34.5 MTOE, accounting for 30.4% of the TFEC, which was followed by the household (residential) sector at 29% and the industry sector at 21.9%. The TFEC of the commercial and agriculture sectors are lower, amounting to 18.7% together. Between 2007 and 2017, the share of the TFEC of the transportation sector slightly decreased by about 2.4% annually, but always remained to be the highest share. It fluctuated between 30% and 32%, with exception of 2014, at 34% of the TFEC. The drop in TFEC in 2014 may be explained by the high price of global oil and energy price, which originated from the growing investment in renewable energy. Meanwhile, the share of the TFEC of the industry sector decreased in both absolute and percentage terms, from 35.9 MTOE being equivalent to 27.8% of the TFEC in 2007 to 24.9 MTOE (21.9% of the TFEC) in 2017. The absolute value of TFEC for household activities was around 33 MTOE between 2007 and 2017, accounting for about 28% of the TFEC, on average. In general, its share increased by 3.9 percentage points during the same period. Another recognizable change was in the commerce and public service sectors, which accounted for 11.8% in 2007, and increased to 16.1% in 2017. Figure 7 presents the TFEC by sectors in percentage points and absolute terms between 2007 and 2017.

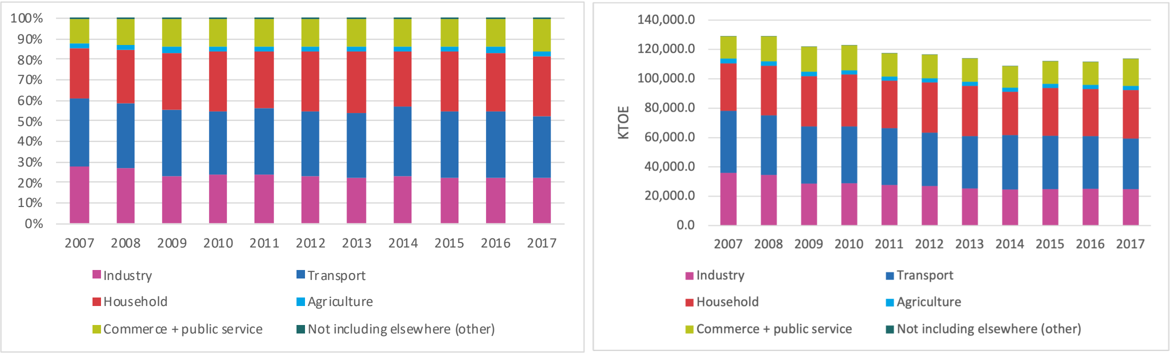

Figure 7. Total final energy consumption by sectors between 2007 and 2017 in percentage points (left) and absolute terms (right)

- Natural gas

According to the Italian Energy Balance Tables, the total natural gas supply in 2017 was 61.5 MTOE, accounting for 37.7 % of the TES (MISE, 2017). The natural gas reserve of Italy is scarce and the country is highly dependent on imported natural gas. More than 90% of the total natural gas supply is imported. In 2017, the net import of natural gas was 56.8 MTOE. Most of the imported natural gas to Italy came from Russia (43.1%). Another part came from Algeria (12.2%), Libya (11.7%), Netherlands (11.7%), Qatar (7.9%) and others. Exported natural gas of Italy is inconsiderable, at 0.2 MTOE, about 41.5% of which was exported to Switzerland, and the remaining was exported to Slovenia (29.5%) and Austria (29.1%) (IEA, 2016).

There are five natural gas pipelines (Transmed, Greenstream, TAG, TENP/ Transit gas, Italy- Slovenia) with five entry points for importing gas. The total import capacity is 298.6 million m^3 per day or 109 billion m^3 per year. The two entry points of Tarvisio and Passo Gries account for 60% of gas imports (IEA, 2016).

The gas transmission network includes 34 thousand km and Snam is the largest gas transmission company, being responsible for 95% of the gas transmission network, with 32306 km of the pipeline (IEA, 2016).

There is 2.5 million km of gas distribution pipelines with 24 million delivery points. Annually about 29 billion m^3 of gas have been delivered. In 2013, there were 222 gas distributors and the top ten operators owned more than 65% of the market. However, there is a trend of reducing the number of gas distributors. In 2014, Italgas S.p.A is the largest gas distribution company, accounting for 24.7% of the gas distribution market, with 52.5 thousand km of network and 5.9 million active delivery points (IEA, 2016).

The total natural gas consumption in 2014 was 61.9 billion m^3, of which 35.2% of natural gas is used for power generation. The second largest consumption of gas is for the residential sector, with 29.9%, as natural gas is the preferred choice for domestic uses in buildings. It was followed by the sector at 17.9%, and other sectors at 12.1% including agriculture, commerce and public service. Other energy industries and transport used a small amount of natural gas, at about 2.9% and 2.1% of total consumption, respectively (IEA, 2016).

- Oil and petroleum products

The total crude oil supply in 2017 was 70.1 MTOE, of which 5.9% of crude oil was domestically supplied. Import of crude oil was 66.3 MTOE, while its export was 0.7 MTOE (Energy Balance Tables).

The total oil and petroleum products consumption was 51.6 MTOE. Most of these products were used for transportation, up to 63.5%. The industry sector used about 16.5% of the total consumption, another 7.8% was used for power generation and 2.8%, for other energy industries and energy own use. The agriculture and residential sectors’ consumption were insignificant, accounting for 5.2% and 4.2% of the total consumption, respectively (IEA, 2016).

- Electricity and heat

In 2015, the total electricity generation of Italy was 283 TWh. During the period 2010-2019, the total electricity generation fluctuated around 292 TWh. About 60% of electricity is originated from fossil fuels, of which 45.1% of electricity and heat generation come from natural gas. The share of fossil fuels is decreasing in the same period and is being replaced by solar and wind power. Figure 8 presents the change in the power generation mix since 1990 (IEA, 2016).

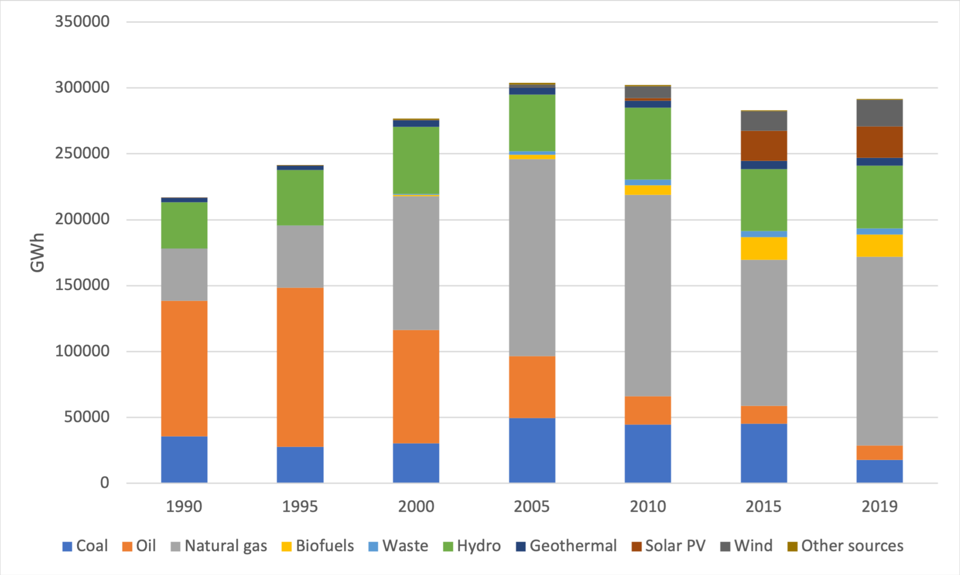

Figure 8. Change in power generation mix between 1990 and 2019

Renewable electricity generation in Italy is made up of biofuel, waste, hydro, geothermal, solar, wind and other sources. The share of renewable electricity increased from 27.5% in 2010 to 41% in 2019. Among the types of renewable energy, the shares of biofuels, solar and wind increased sharply, contributing considerably to the renewable electricity growth in the same period. Specifically, the electricity by biofuels increased from just above 2.4% in 2010 to 5.7% in 2019. The largest increase was in solar PV, from less than 1% of total renewable electricity generation in 2010, to 8.1% in 2019. Another sharp increase was wind power, doubling from 3% in 2010 to 6.9% in 2019 (IEA, 2020) (IEA, 2020a, 2021). Figure 9 presents the shares of renewable electricity from 2010 to 2019 (IEA, 2020a; Terna, 2017).

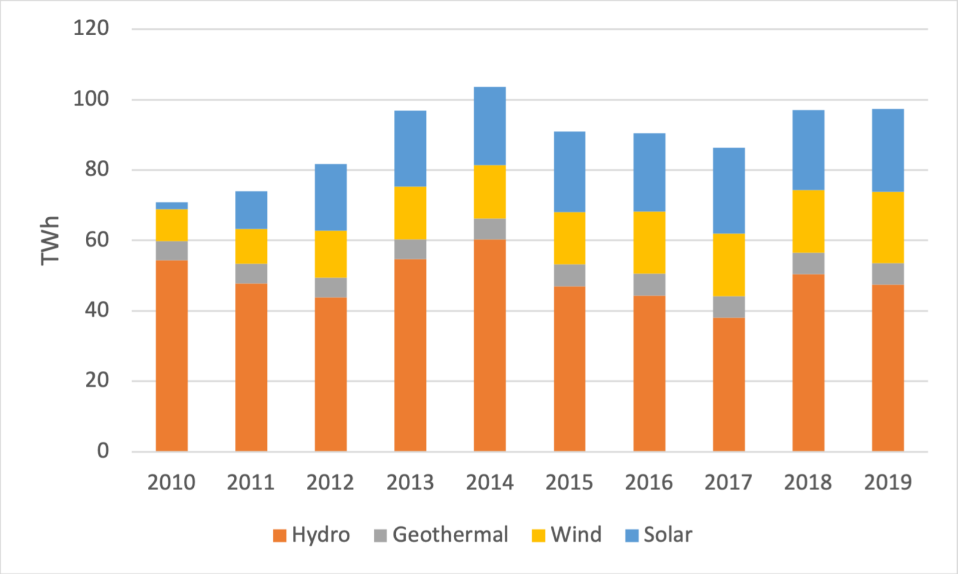

Figure 9. Share of renewable power between 2010 and 2019

Italy is the largest importer of electricity in Europe. The net electricity import of Italy accounted for 2.6% of the TPES, and was unchanged during 2005-2015. Italy is connected to the EU network by 25 high voltage interconnectors, including four with France, 12 with Switzerland, two with Austria, two with Slovenia, two DC and one subsea with Corsia, one DC subsea with Greece, one AC subsea with Malta and one DC subsea with Montenegro (IEA, 2016).

Terna is the Transmission System Operator, TSO, in Italy. It controls 63.5 thousand km of high voltage network. The distribution of electricity is under the control of Enel and more than 130 other Distribution System Operators, DSOs. There are about 387 thousand km of medium-voltage lines and 852 thousand km of low-voltage lines. 37% of low-voltage lines is underground (IEA, 2016).

Table 1 The electricity generation mix of Italy in 2017 (Terna, 2017)

Table 1 . Electricity generation mix of Italy in 2017 (Terna, 2017)

Input fuel	**Technology**	**In percentage**
bituminous coal	ELE	9.79
bituminous coal	CHP	0.04
sub-bituminous coal	ELE	0.01
coke oven gas	CHP-IC	0.01
coke oven gas	CHP-CC	0.14
coke oven gas	CHP-CS	0.10
blast furnace gas	CHP-IC	0.02
blast furnace gas	CHP-CC	0.24
blast furnace gas	CHP-CS	0.18
other recovery gas	CHP-CC	0.03
other recovery gas	CHP-CS	0.02
refinery gas	CHP-IC	0.01
refinery gas	CHP-GT	0.11
refinery gas	CHP-CC	0.36
refinery gas	CHP-CP	0.03
refinery gas	CHP-CS	0.06
gas oil and diesel oil (w.o biofuel)	ELE-IC	0.01
gas oil and diesel oil (w.o biofuel)	ELE-CS	0.11
gas oil and diesel oil (w.o biofuel)	CHP-CC	0.02
fuel oil	ELE-IC	0.05
fuel oil	ELE-CS	0.40

fuel oil	CHP-GT	0.01
fuel oil	CHP-CC	0.03
fuel oil	CHP-CS	0.01
other oil product	ELE-CS	0.03
other oil product	CHP-CC	2.21
natural gas	ELE-IC	0.08
natural gas	ELE-GT	0.16
natural gas	ELE-CS	0.11
natural gas	ELE-CC	15.79
natural gas	CHP-IC	2.73
natural gas	CHP-GT	1.37
natural gas	CHC-CC	21.61
natural gas	CHP-CP	0.21
natural gas	CHP-CS	0.25
hydro	ELE	10.91
wind	ELE	5.35
solar	ELE	7.35
geothermal	ELE	1.87
primary solid biofuels	ELE-IC	0.09
primary solid biofuels	ELE-CS	0.58
primary solid biofuels	CHP-IC	0.17
primary solid biofuels	CHP-CP	0.06
primary solid biofuels	CHP-CS	0.37
biogas	ELE-IC	0.88
biogas	ELE-GT	0.01
biogas	CHP-IC	1.60
biogas	CHP-CC	0.01
renewable municipal waste	ELE-IC	0.35
renewable municipal waste	CHP-IC	0.11
renewable municipal waste	CHP-CP	0.04
renewable municipal waste	CHP-CS	0.23
other liquid biofuels	ELE-IC	0.31
other liquid biofuels	ELE-CC	0.61
other liquid biofuels	CHP-IC	0.12
other liquid biofuels	CHP-CP	0.04
other liquid biofuels	CHP-CS	0.25
industrial wastes	ELE-CS	0.02
industrial wastes	CHP-CS	0.01
non-renewable municipal waste	ELE-IC	0.35
non-renewable municipal waste	CHP-IC	0.11

non-renewable municipal waste	CHP-CP	0.04
non-renewable municipal waste	CHP-CS	0.23
import from AT		0.38
Import from CH		5.53
Import from FR		3.68
Import from GR		0.08
Import from SI		1.71
other sources		0.21
Total		**100.00**

Notes

ELE	*electricity production*
CHP	*heat power cogeneration*
IC	*internal combustion*
CC	*combined cycle*
CS	*condensing steam*
GT	*gas turbine*
CP	*counter pressure*

In 2014, electricity consumption is roughly equally shared among Industry (38.8%), commerce and other services (32.2%). The residential sector consumes about 22.1%. The consumption for transport and other energy uses is insignificant, at 3.6% and 3.3%, respectively (IEA, 2016). By 2018, these shares do not change much, at 39.6% of electricity for industrial activities, 32.2% of electricity for commerce and other service and 22.2% of electricity for the residential sector (IEA, 2020b).

2.2.3. Some highlights on Italian energy and electricity supply and demand

In 2017, the Italian primary energy supply is fossil fuel intensive, with 88% of the primary energy supply from fossil fuels, mainly oil, petroleum products and natural gas. Meanwhile, energy production is ‘green’, with nearly 70% of energy being produced from renewable sources, mainly solid biofuels and geothermal.

The security of the energy supply is at risk and the country is highly dependent on imports. Domestic energy production accounts for about 19.5% of the primary energy supply in 2017. About 94% of the oil and petroleum products and 90% of the natural gas supply is imported in the same year. Fortunately, it is expected that Italy will be less dependent on energy imports as the TES has been decreasing and domestic energy production has been increasing during 2007-2017.

By 2040, the national energy production is expected to be greener, as the share of renewable energy out of PEP has been increasing during 2007- 2017. Moreover, the same expectation occurs in the national energy consumption. Firstly, both TES and the share of fossil fuels (out of the TES) have been decreasing over the period 2007- 2017. Secondly, though RE supply accounts for only one-fifth of the TES, its share has been increasing in the same period.

The final energy consumption is mostly for transportation with high demand for oil and petroleum products. The final energy consumption is expected to decrease due to the impacts of Covid-19 and the war in Ukraine (in the short-term), and improvement in electricity and energy performance by 2040.

The Italian electricity sector depends on natural gas, and the share of fossil fuel-based electricity is decreasing and being replaced by solar and wind power. In 2019, the share of renewable electricity was up to 41% of the total electricity generation.

2.3. Production cost of electricity

This part analyses the production cost of electricity from different sources in Italy. Conventionally, in the electricity sector, most of the value comes from electricity generation process, in forms of capital and operational expenditures. Though there are some other costs such as transmission and distribution of electricity, the storage cost for variable renewable electricity (which will increase as a large amount of variable renewable electricity is integrated into the system), these costs are not reported in this chapter as well as included in the simulation. This is one of the limitation of the study, which will be further discussed at the end of the thesis. Moreover, only electricity with input fuels contributing to more than 1% is screened.

2.3.1. Natural gas

In this work, the natural gas considered is the amount that is used for generating electricity only (ELE) and that is used for co-generation of electricity and heat (CHP). For each of these, two technologies are considered (combined cycle and standard turbines). So, there are four technologies fuelled by natural gas, in total.

The report on long-term projections of the techno-economic performance of CHP indicated the investment cost of 1.2 million Euro/MW, the annual fixed operation and maintenance (O&M) cost of 5 thousand Euro/MW, and the variable O&M cost of 5 Euro/MWh by 2020 for combined cycle technology. For the conventional cycle, the investment cost is much lower, at 0.45 million Euro/ MW, but the O&M cost is higher, at 7 thousand Euro/ MW for the annual fixed O&M cost and 7 Euro/MWh for the annual variable O&M cost. The average lifetime for natural gas-fired CHP is 20 years

(Alberici et al., 2014). The share of investment cost of natural gas-fired CHP technologies (Grosse et al., 2017) is presented in Table 2.

Table 2. Investment cost of natural gas fired power and CHP generation technologies

Technology cost	Natural gas fuelled CHP		Natural gas fuelled power	
	Combined cycle	Standard	Combined cycle	Standard
- Investment (mil. Euro/MW)	1.2	0.45	0.49	0.27
Main equipment	26%	24%		
Balance of plant	24%	21%		
Electrical and Information and communication (I&C) supply and installation	10%	13%		
Civil and structural	8%	9%		
Project indirect	7%	7%		
Development	14%	14%		
Interconnection	6%	7%		
Insurance and other	5%	5%		
Investment cost (Eur/MWh)			3.49	5.35
Decommissioning (Eur/MWh)			0.07	0.1
- Fixed O&M (thousand. Euro/ MW annually)	5	7		
- Variable O&M (Eur/ MWh)	5	7		
Fuel (Eur/ MWh)			38	62
Carbon (Eur/ MWh)			8	14
Other O&M costs (Eur/MWh)			6	9

For ELE technologies, the report of Ecofys's expert on European electricity generation technology in 2014 indicated the levelized cost of electricity (LCOE) from combined cycle technology is 113 Eur/MWh with the efficiency of 60% (Alberici et al., 2014). This number is much higher than the updated estimation of the International Energy Agency (IEA) and the OECD Nuclear Energy Agency (NEA) in 2020, which indicated the LCOE of the same technology with the same efficiency in Italy, ranging from 66.83 to 71.88 USD/ MWh, depending on the discount rate of 3% to 10% (IEA and NEA, 2020). The estimation of IEA and NEA is more updated and nation-specific, thus this estimation is selected, and converted into EUR 2020.

In the case of standard technology of gas turbines, the report of Ecofys for European electricity generation technologies indicated the LCOE of 26 EUR/MWh at 49% efficiency (Alberici et al., 2014), while that of IEA and NEA report ranges between 108.03 and 115.3 USD/MWh at the efficiency of 37% (IEA and NEA, 2020). For the same justification as above, the estimation of IEA and NEA is selected and converted into EUR 2020.

The average lifetime of ELE technologies fuelled by natural gas is 30 years. Table 2 presents the cost of these technologies.

2.3.2. Hard coal

The McKinsey‘s report for German hard coal power plants indicated an investment cost ranging from 1.4 to 1.6 million EUR/MW, fixed O&M was at 14 thousand EUR/MW annually and variable O&M was at 1 EUR/MWh in 2020 (McKinsey, 2010). Another Danish study with full load condensing power capacity and cooling with sea water reported a slightly higher cost, with the investment cost of 1.8 million EUR/ MW, fixed O&M of 31 thousand EUR/MW annually and variable O&M of 2.75 EUR/ MWh in 2020 (Danish Energy Agency and Energinet, 2016). Ecofys reports a wide range of technology costs in Europe, from 1.01 to 2.09 million EUR/ MW of investment cost, and from 2 to 15 EUR/MWh of O&M cost. The average investment cost is 1.58 million EUR/MW and 7 EUR/MWh, at the efficiency of 45% (Alberici et al., 2014).

The average lifetime of a hard coal thermal power plant is 40 years (Alberici et al., 2014; McKinsey, 2010).

Table 3 presents the investment cost of coal-fired power generation technologies.

Table 3. Investment cost of coal-fired power generation technologies

Technology	Efficiency (%)	Overnight cost (USD /kW)	Investment cost (USD/MWh)			Decommission (USD/MWh)			Fuel (USD/ MWh)	Carbon (USD/ MWh)	O&M (USD/ MWh)
			Discount rate 3%	Discount rate 7%	Discount rate 10%	Discount rate 3%	Discount rate 7%	Discount rate 10%			
Combined cycle turbine at 85% of capacity factor	60%	590	4.17	6.85	9.28	0.08	0.04	0.02	45.5	10.1	6.99
Standard gas turbine at 30% capacity factor	37%	325	6.4	10.3	13.76	0.12	0.06	0.03	73.98	16.42	11.11

2.3.3. Oil

In Italy, oil is used to cogenerate both electricity and heat. In the report of the European Commission (Grosse et al., 2017), the investment cost and O&M cost of oil-fired CHP technologies are presented in Table 4. The average lifetime of an oil-fired CHP plant is 25 years.

Table 4. Investment cost of oil-fired power and heat generation technologies

Oil fired CHP	
- Nominal investment (mil. Euro)	1.99
Main equipment	30%
Balance of plant	26%
Electrical and I&C supply and installation	8%
Civil and structural	7%
Project indirect	7%
Development	12%
Interconnection	5%
Insurance and other	5%
- Fixed O&M (thousand. Euro/ MW annually)	9
- Variable O&M (Eur/ MWh)	0.6

2.3.4. Hydro

According to the report on power generation technologies of McKinsey, the cost of hydropower in Italy is presented in

Table 5. The average lifetime of a hydropower plant is 50 years (McKinsey, 2010).

Table 5. Investment cost of hydropower technologies

Technology	Net capacity (Mw)	Capacity factor (%)	Overnight cost (USD/kW)	Investment cost (USD/kW)			Decommission (USD/MWh)			O&M (USD/MWh)
				Discount rate 3%	Discount rate 7%	Discount rate 10%	Discount rate 3%	Discount rate 7%	Discount rate 10%	
Reservoir, alpine region <5MW	0.32	65%	3,966.00	4,274.00	4,719.00	5,079.00	0.10	0.01	0.00	16.85
Reservoir, alpine region >=5MW	15.00	38%	3,108.00	3,349.00	3,697.00	3,980.00	0.14	0.01	0.00	18.37
run of river < 5MW	0.02	55%	6510	7015	7745	8336	0.2	0.02	0.003	24.64
run of river < 5MW	0.1	34%	3013	3247	3585	3859	0.15	0.01	0.002	17.01
run of river < 5MW	0.2	55%	5503	5930	6547	7047	0.17	0.02	0.002	21.47
run of river < 5MW	0.25	15%	3647	3930	4339	4670	0.14	0.01	0.002	22.09
run of river < 5MW	0.25	8%	3266	3520	3886	4183	0.42	0.04	0.006	29.18
run of river < 5MW	0.25	19%	1592	1715	1894	2039	0.66	0.06	0.009	51.07
run of river < 5MW	0.5	20%	1070	1153	1273	1370	0.09	0.01	0.001	13.01

run of river < 5MW	0.5	15%	3782	4075	4499	4843	0.42	0.04	0.006	17.52
run of river < 5MW	0.5	22%	2398	2584	2853	3071	0.19	0.02	0.003	12.07
run of river < 5MW	0.7	55%	4411	4753	5248	5649	0.14	0.01	0.002	12.47
run of river < 5MW	1	15%	956	1030	1137	1224	0.11	0.01	0.002	8.71
run of river < 5MW	2.1	50%	3216	3466	3826	4119	0.11	0.01	0.002	8.42
run of river >= 5MW	5	37%	3052	3289	3631	3908	0.14	0.01	0.002	27.53

2.3.5. Geothermal

Geothermal is a capital-intensive technology. Its operating cost is low and predictable. The engineering, procurement, and construction costs of geothermal follow the trends in commodity prices and drilling costs. When the costs of commodity and oil increase, the cost of geothermal power increases too. Vice versa, the cost of geothermal power decreases, but slowly.

Investment costs include the cost of exploration and resource assessment, drilling cost, reinjection cost, additional working capital, field infrastructure, geothermal fluid collection and disposal system and other surface installation, cost of project development and grid connection cost. Among these cost components, the cost for drilling accounts for 60% to 90% of the total investment cost.

The average lifetime of a geothermal power plant is 30 years.

In 2020, the cost of geothermal in Italy is reported in

Table 6 (IEA and NEA, 2020).

Table 6. Investment cost of geothermal, wind and solar PV technologies

Technology	Net capacity (Mw)	Capacity factor (%)	Overnight cost (USD/kW)	Investment (USD/MWh)			Decommission (USD/MWh)			O&M (USD/ MWh)
				Discount rate 3%	Discount rate 7%	Discount rate 10%	Discount rate 3%	Discount rate 7%	Discount rate 10%	
Geothermal	40	76%	3851	26.65	50.04	72.42	0.37	0.13	0.06	17.96
	15	86%	7132	43.69	82.06	118.76	0.6	0.22	0.09	21.25
	10	86%	9799	60.03	112.74	163.17	0.83	0.3	0.13	23.02
	5	86%	10959	67.14	126.09	182.48	0.93	0.33	0.14	25.38
Wind onshore>1MW	1	39%	3022	51.02	76.24	97.88	1.17	0.63	0.39	14.56
	10	37%	1429	25.19	37.65	48.33	0.58	0.31	0.19	14.91
	20	30%	1499	32.91	49.17	63.13	0.75	0.41	0.25	9.94
Wind onshore<1MW	0.01	17%	5317	201.93	301.74	387.39	4.61	2.51	1.55	591.75
	0.02	32%	5539	104.51	156.17	200.49	2.39	1.30	0.80	27.55
	0.06	20%	4075	112.98	168.82	216.74	2.58	1.41	0.87	41.87
	0.06	33%	4616	132.57	198.09	254.32	3.03	1.65	1.02	41.46

	0.1	31%	3323	90.52	135.26	173.66	2.07	1.13	0.70	39.28
	0.19	18%	2852	70.76	105.73	135.74	1.62	0.88	0.54	29.29
	0.5	33%	2659	52.14	77.90	100.02	1.19	0.65	0.40	20.38
	0.8	32%	1782	36.90	55.13	70.78	0.84	0.46	0.28	19.69
	0.83	30%	2269	50.36	75.24	96.60	1.15	0.63	0.39	12.91
	0.9	48%	2727	37.17	55.54	71.30	0.85	0.46	0.29	15.37
	0.9	43%	2786	42.08	62.88	80.72	0.96	0.52	0.32	15.61
solar photovoltaics (residential)	0.004	20%	1846	65.14	96.45	123.1	10.26	13.3	16.01	166.34
	0.01	17%	1368	55.06	81.52	104.05	1.26	0.68	0.42	58.06
solar photovoltaics (commercial)	0.08	20%	1306	46.07	68.22	87.07	9.26	12.27	14.88	21.28
	0.21	17%	907	36.48	54.01	68.93	0.83	0.45	0.28	16.67
	0.42	20%	1210	42.71	63.23	80.71	9.19	12.23	14.85	18.44
solar photovoltaics (utility scale)	0.83	20%	827	29.11	43.1	55.02	0.67	0.36	0.22	14.76
	0.83	27%	836	21.77	32.23	41.13	2.51	3.14	3.72	27.85

2.3.6. Wind

The report of the International Renewable Energy Agency (IRENA) indicated the global investment cost of wind power was 1.56 million USD/MW in 2015 (IRENA, 2016), which reduced to 1.456 million USD in 2016 and 1.379 million USD in 2017 (IRENA, 2018). In Italy, the average investment cost of wind power is higher than the global average, at 1.694 million USD/MW. Within the investment cost, the cost for wind turbine accounts for up to 75%, which includes the costs for rotor blades, gearbox, generator, power converter, nacelle, tower and transformer. Other investment costs, such as the costs for civil works (construction work for site preparation and foundation for towers), grid connection (transformer, substations, and connection to the local distribution and transmission network), planning and project (development cost and fees, licenses, financial closing costs, feasibility and development studies, legal fees, owners' insurance, debt service reserve and construction management), account for 4.5%, 5% and 15.5% respectively (IRENA, 2018).

O&M cost for wind power technology accounts for 20% - 25% of its LCOE, which is 50 USD/kW on average in Italy. The O&M cost includes the cost for salary (13%), maintenance (67%), land lease, local tax, insurance, site security (13%), admin cost and utility (8%).

The investment cost of wind power can be found in

Table 6.

2.3.7. Solar

The report of IRENA indicated the global average installation cost of solar power was 1.8 million USD/MW in 2015 (IRENA, 2016), which reduced to 1.388 million USD/MW in 2017 (IRENA, 2018). The same cost in Italian context is 1.159 USD/MW. These costs include cost for hardware (module 42%, inverter 9%, cables 5%, grid connection 8%, monitoring and control 1%, racking and mounting 7%, safety and security 1%), installation (electrical installation 8%, inspection 1% and mechanical installation 6%) and soft cost (financing cost 3%, incentive application 1%, margin 3%, permitting 3%) (IRENA, 2018).

The O&M cost of solar power is about 10 – 18 USD/kW, about half of which is for operation and maintenance of the system, 18% for land lease, 15% for local tax, 7% for insurance, 4% for site security, 5% for admin cost and 2% for utility.

The investment costs for solar PV power can be found in

Table 6.

2.3.8. Biogas

In Italy, biogas is used for generating both heat and power. The investment cost for biogas CHP technology is 0.8 million Eur/ MW, 26% of which is for main equipment, 21% for the balance of the plant, 8% for electrical, I&C supply and installation, 12% for civil work, 7% are indirect costs, 15% for development, 6% for interconnection, 5% for insurance and others. Fixed O&M of biogas CHP is 9 thousand Eur/MW and variable O&M is 13.1 Euro/MWh (IRENA, 2018).

2.3.9. Discount rate

The selected discount rate is 3%.

2.3.10. Exchange rate

The exchange rate of USD and EUR in 2020 ranges from 1.1634 to 1.2338 USD per 1 EUR. The average exchange rate is 1.1955 : 1 in 2020 (ECB, 2021)[6].

2.3.11.Inflation rate

The Euro has had an average inflation rate of 1.06% annually since 2015. The detailed discounted rate, exchange rate, and inflation rate of the Euro is specified in Table 7 (ECB, 2021)[7].

Table 7. Inflation rate between 2015 and 2021

	2015	2016	2017	2018	2019	2020	2021
Discounted rate	1.29-2.2	1.18-1.94	1.79-2.4	2.77-3.47	0.9-2.98	0.58-1.8	0.58-1.07

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[6] https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html

[7] https://sdw.ecb.europa.eu/quickview.do?SERIES_KEY=229.IRS.M.IT.L.L40.CI.0000.EUR.N.Z

https://sdw.ecb.europa.eu/quickview.do?org.apache.struts.taglib.html.TOKEN=a78b51e012ecadaa1ca8b665d3ec857b&SERIES_KEY=120.EXR.D.USD.EUR.SP00.A&start=01-01-2015&end=31-12-2021&submitOptions.x=0&submitOptions.y=0&trans=N

https://www.ecb.europa.eu/stats/macroeconomic_and_sectoral/hicp/html/index.en.html

Exchange rate (USD/EUR)	1.20-1.05	1.04-1.15	1.04-1.20	1.13-1.24	1.09-1.14	1.11-1.21	1.12-1.23
Inflation rate	0.03	0.24	1.53	1.75	1.2	0.25	1.4

2.4. Energy environment policy

2.4.1. Zero-carbon pathway

All sectors of the economy have a certain role in the transition towards 'carbon-neutrality'. The key sectors which compose of the energy industry, transport, manufacturing industries and construction, are all related to fuel combustion. In Italy, 80.5% of the national GHG emissions excluding LULUCF in 2019 are from the energy sector, which includes 21.9% from energy industries, 25.2% from transport activities and 11.9% from energy combustion in manufacturing industries and construction sectors (ISPRA, 2021).

As a consequence, all zero-carbon pathways converge on one central element, namely, that the energy system needs to change radically towards decarbonization. In the energy industries, the deployment of renewable energy together with the electrification of the energy system, and the production of carbon-free fuels and feedstock for industry and transportation will contribute to the zero-carbon pathway.

In the transport sector, apart from carbon-free fuel solutions, an integrated approach is needed for achieving deep emissions reductions, including increasing vehicle efficiency, low and zero-carbon vehicles and infrastructures, increasing efficiency of the transport system, changes in behaviour and consumer choice to shift from private transportation to low carbon public transportation, shared mobility and zero carbon mobility (biking and walking).

In manufacturing industries, GHG emissions come from both energy use and industrial processes. Emissions from energy use in industries can be reduced by improving energy efficiency and switching to low and carbon-free energy sources such as renewable electricity, sustainable biomass, carbon-free fuels and feedstock. Meanwhile, emissions from industrial processes are more difficult to reduce. Cutting these emissions would require deep technological and systematic innovation, such as carbon capture and storage, resource efficiency, reusing, recycling and a circular economy approach.

The Italian climate and energy framework is under the EU-wide targets and policy objectives. In July 2021, the EU commission adopted the "Fit for 55" package to raise the 2030 CO_2 emissions reduction target to at least 55% as compared to the 1990 level, and to aim at carbon neutrality by 2050 (EC, 2021)[8]. The package looked at the actions required across all sectors including energy efficiency and renewable energy.

Some key points of the Fit for 55 package include:

- Reduction of primary energy by 39% compared to the 1990 level, being equivalent to a consumption of no more than 1,023 million TOE by 2030;
- Increase the share of renewable energy in final energy consumption from 32% to 40% by 2030.
- A revision of the EU Emission Trading System (ETS), to include land transport and buildings.
- In the transport sector, the progressive reduction of GHG emissions from cars and vans is planned to bring the zero-emissions transport sector by 2035. This implies that no new vehicle, diesel petrol or hybrid is sold anymore from that date, indicating that there will be mass production of electric vehicles as well as a drastic reduction of their price.
- The creation of a Carbon Border Adjustment Mechanism (CBAM), which applies a CO_2 tax on the import of cement, iron, steel, aluminium, fertilizers and electricity if they are not produced with adequate standards as compared to emissions.
- Revision on minimum taxation of energy production
- Revision of the regulation on the use of land and forest, relating to the emissions by capturing or releasing GHGs
- Revision of regulation on "Effort Sharing", relating to the GHG emission reduction in sectors not covered by the ETS

2.4.2. National energy environmental policy framework

In Italy, the environment policy framework is defined through four main documents: the Integrated National Energy and Climate Plan (MISE et al., 2019), the National Energy Strategy (Ministry of Economic Development, 2017a), the Energy Efficiency National Action Plan (Ministry of Economic Development, 2017b), and the National Renewable Energy Action Plan (Ministry of Economic Development, 2010).

- The Integrated National Energy and Climate Plan (NECP)

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[8] https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/

The NECP is mandated by the European Commission (EC) to each member state to achieve GHG emission reduction targets. The NECP includes five dimensions:

- Energy efficiency,
- Renewables,
- GHG emission reductions,
- Interconnections,
- Research and innovation.

The Italian NECP has been approved in 2019, but it needs to be updated after the Fit for 55 package for the period 2021-2030, establishing objectives, measures and elements corresponding to five dimensions of the EC.

Key objectives include:

- Accelerate the decarbonization process and achieve full decarbonization of the energy sector by 2050;
- Place a central emphasis on citizens and businesses;
- Developing the energy system towards distributed renewable sources;
- Promoting the frameworks, infrastructure and market rules for the integration of renewables;
- Ensure energy security with an adequate supply of conventional sources;
- Promote energy efficiency across all sectors;
- Promote electrification of consumption, especially in the civil and transportation sectors;
- Conducting research and innovation activities;
- Take into account the strategic environmental assessment and related environmental monitoring and measures for avoiding negative impacts on air, water and soil of energy transition;
- Continue the process of integrating the national energy system with the energy union.

Key measures include:

- Careful governance of the plan for ensuring the uniformity of actions;
- Actions need to streamline with the measures and defined timeframe;
- Updating tasks of public bodies;
- Promoting research activities;
- Integrating new technologies;
- Considering additional instruments;
- Using flexible mechanisms.

This Plan also reinforced the national commitment to emission reduction targets and energy-saving measures. By 2020, Italy committed to reducing 21% of global GHG emissions in the Emission Trading System (ETS) and 13% in the non-ETS compared to 2005. By 2030, the targets are set to 43% and 33% reductions compared to 2005 level, respectively.

2.4.3. The National Energy Strategy (SEN)

The SEN was adopted in March 2013, defining objectives, key policies and priority measures to improve the competitiveness and sustainability of the Italian energy sector by 2020 and 2050.

Four key goals include:

- Reducing energy costs by aligning prices to EU average prices;
- Meeting and going beyond EU targets set out in the 2020 EU climate-energy package and the Italian national action plan of June 2010;
- Improving supply security with a reduction in foreign dependency from 84% to 67% of total energy needs;
- Boosting growth and employment by mobilizing investment of 170-180 billion Euro by 2020, either in traditional sectors or in the green economy.

In this document, the GHG emission reduction target for 2020 is set to be 18% compared to 2005 emissions, exceeding the European objectives for Italy.

In 2017, the core target of SEN was updated to 2030, including reducing final energy consumption by 10 MTOE, reaching 28% of renewable energy share and 55% of renewable power.

2.4.4. The Energy Efficiency National Action Plan (PAEE)

The PAEE is prepared by the EU member states, setting out estimated energy consumption, planned energy efficiency measures and the improvements individual EU member states expect to achieve. Under the EU Energy Efficiency Directive, states must draw up these plans every three years.

The second Italian PAEE was approved in 2014, clarifying the national targets for the reduction of primary and end-use energy consumption. It specifies the savings in end-uses of energy expected in 2020 by economic sectors and by the main energy efficiency promotion scheme. The third Italian PAEE was adopted in July 2017, reporting the achieved progress.

Economic sectors being covered under PAEE include:

- Residential,

- Tertiary (public and private),
- Industry, and
- Transport.

Measures under PAEE:

- Energy efficiency obligation schemes and alternative policy measures: the white certificates obligation scheme to create an obligated market for energy efficiency certificates in electricity and gas distributors, the tax relief on refurbishment and renovations to improve the energy efficiency of buildings, and the thermal energy account to encourage public authority, businesses and households to implement energy efficiency improvement actions in buildings and technical installations;
- Compulsory energy audits for large enterprises and energy-intensive enterprises and incentives on energy management systems for small and medium-sized enterprises (SMEs);
- Metering and billing;
- Consumer information and training programs;
- Qualification, accreditation and certification schemes;
- Energy services including an integrated service set of management, maintenance and energy efficiency of thermal and electrical installations provided by Energy Service Company (ESCO);
- Other policy measures: energy performance contracts for buildings; split incentives to share costs and benefits among user, building owner and ESCO.

2.4.5. The National Renewable Energy Action Plan (NREAP)

The NREAP was developed in line with the Directive 2009/28/EC on the promotion of the use of energy from renewable sources. Under the provisions of the Directive, each member state needs to set an individually binding renewable energy target, which will contribute to the achievement of the overall EU's 20% renewable energy target.

The Italian NREAP was adopted in 2010 and its overall target is to achieve 17% of final energy consumption from renewable sources by 2020, being equivalent to 22.62 MTOE.

Mechanisms under the NREAP include:

- Tax relief of 55% on the cost incurred for the installation of heat pumps, solar thermal systems or biomass systems;
- The obligation for new buildings (not yet fully operational) to cover 50% of their energy needs for domestic hot water and electricity with renewable sources;

- Tax relief for the users connected to district heating networks using geothermal or biomass
- Energy efficiency credit scheme for technology such as solar thermal systems, biomass boilers and heat pumps
- Duty exemption for solid biomass for domestic boilers
- The obligation of biofuel share out of conventional fuel consumption for transportation. This share increases over time. Emphasis was put on second-generation biofuel for sustainability purposes.
- Measures such as national regulations, and technical regulations for supporting the wholesale use of 25% biodiesel mix in public transport fleets.
- The green certificate schemes for power plants are based on a minimum quota of new electricity production from renewable sources.
- Fixed all-inclusive tariffs for electricity fed into the grid by renewable energy plants with a maximum power output of 1 MW (0.2 MW for wind energy)
- Feed-in tariffs for photovoltaic and solar thermodynamic plants
- Simplified means of selling energy produced and fed into the grid at a fixed market price.
- Possibility of placing greater value on energy produced through the net metering mechanism for plants with a maximum power output of 200kW;
- Dispatch priority for renewable sources;
- Connection to the electricity network within pre-set deadlines and under advantageous conditions for plant operators;
- Measures to modernisation and expansion of the electricity transmission and distribution network;
- Measures to simplify the authorization procedures
- Cooperation with other countries for the fulfilment of the national renewable energy use obligation;
- Promoting research and innovation for ensuring the growth in the use of renewables, reduction in costs and development of industrial and employment opportunities;
- Measures on monitoring and publication of information;

2.5. Energy development scenarios

2.5.1. Energy efficiency (EE) and Renewable Energy (RE) targets

The EE targets are put forward in several official documents: the NECP 2019 and SEN 2013 set global targets for 2011-2020; and the PAEE (2011, 2014 and 2017) clarified the distribution by sector of the SEN targets and specified the progress already made. Specifically, these documents indicated the targets of reduction by 2020 in primary energy consumption by 24% as compared to the PRIMES 2007 scenario, exceeding the European target by 20% (SEN 2013 and NECP 2019) and in final energy consumption by 1.5% annually, without transportation sector (NECP 2019). In absolute terms, the primary energy savings by 2020 is set to be 20.5 MTOE and that of final energy is 15.5 MTOE.

By 2030, the targets are indicated in NECP 2019 and SEN 2017, including a 43% reduction in primary energy consumption, a 0.8% reduction in annually final energy consumption without the transportation sector and 10 MTOE final energy consumption reduction.

For RE, it is expected that 30% of the gross final consumption of energy comes from renewable sources and 10% of RE in the transportation sector by 2020 (NECP 2019). This target is higher than the target of SEN 2013, at 19-20% of RE share in gross final consumption and the target of NREAP 2010, at 17% of final energy consumption by 2020.

By 2030, the RE target is set in Sen 2017 and NECP 2019, indicating a 28% ~ 30% of the RE share in total energy consumption, 55% of the RE share in electricity consumption and 21% ~ 22% of the RE share in the transportation sector.

The Fit for 55 package set out a proposal to revise EE and RE directives, in which to raise the energy saving by 36% for final energy consumption, 39% for primary energy consumption, and a target of 40% of RE share by 2030[9]. This package has not been fully integrated into the national energy strategy or action plans.

2.5.2. EE and RE progress

According to the annual reports of the Ministry of Economic Development, until 2020, the TES was 143.552 MTOE, reducing 10.12% compared to that of 2019, and significantly reducing from 184 MTOE in 2017. The role of fossil fuels in the TES reduces, but still accounts for a high percentage of 77% of TES (compared to 88% of fossil fuels in TEP in 2017). The share of natural gas increased slightly to 40.6% of the TES, followed by oil and petroleum products at 33.12% of the TES. The absolute value of renewables out of the TES slightly increase from 28 MTOE in 2017 to 29 MTOE in 2020. However, thanks to the reduction in the absolute value of the TES, the share of RE supply has increased from 12 % in 2017 to 20.22% of the TES in 2020. While the TES reduction is expected to originate from economic recession and Covid consequences on the economy, the reduction in the share of fossil fuels and the corresponding

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[9] https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/

increase in the share of renewables in the TES is due to energy and climate policies which encourage the deployment of renewable energy and energy efficiency in all economic sectors (Ministry of Ecological Transition, 2020; Ministry of Economic Development, 2021, 2017c).

The TFEC in 2020 was 103.604 MTOE, 9.18% lower than those of 2019 or 2017 both around 113 MTOE. Compared to the TFEC of 2019, the strongest reduction is in the consumption of oil and petroleum products (at 17%), followed by solid fossil fuels (at 13.4% reduction), and non-renewable waste (at 9.2% of reduction). Consumption of low-emission fossil fuels and carbon-zero energy including natural gas, wind, solar pv, biofuels and etc reduce at a slower pace, at 5.37% for natural gas and 5.29 for renewables. Similar to TPES, the reduction in TFEC is due to the economic downturn and covid consequences which reduce the transportation demand as well as final consumption in other economic sectors; and the increase in energy efficiency, especially in industry, household and service sectors (Ministry of Ecological Transition, 2020; Ministry of Economic Development, 2021, 2017c).

In terms of electricity production and consumption, the electricity demand in 2020 reported by Terna, mounted at 280.5 TWh, being equivalent to 24.123 MTOE, reducing 4.5% compared to 2019. Nearly 60% of the electricity production was covered by fossil fuels; the remaining include hydro, wind, geothermal, solar pv and bioenergy. While the shares of fossil fuels-based electricity reduced (from 65.8% in 2019 to 57.6% in 2020), the shares of renewable electricity increased slightly, with a 2.8% increase in hydropower, a 5.3% increase in solar PV, and a 0.4% increase in bioenergy). The exceptional case is wind, decreasing by 7.1% and geothermal decreasing by 0.8% (Terna, 2021).

In term of EE in the electricity, the primary energy factor of Italy range between 1.9 and 2.0 during 2012 and 2017, which is lower in summer time and daily hours, with higher integration of variable renewable energy, and vice versa (Noussan et al., 2018).

The detailed EE and RE targets and progress are summarized in Table 8.

Table 8. RE and EE targets and progress (compiled from NECP, SEN, PAEE, NREAP and reports of (Ministry of Ecological Transition, 2020; Ministry of Economic Development, 2021; Terna, 2021))

RE and EE targets and progress	**Unit**	**2016 / 2017 (Achievement)**	**2020 (Target)**	**2020 (Achievement)**	**2030 (Target)**
Reduction in total energy supply				41 MTOE (22%) compared to 2017	
Share of RE in total energy supply		12%		20.22%	
Reduction in primary energy consumption	%		-24		-43 (indicative)
	MTOE/year		20.05		
Primary energy savings in Residential sector	MTOE/year	3.19	5.14		
Primary energy savings in Public Tertiary sector	MTOE/year	0.21	0.8		
Primary energy savings in	MTOE/year		0.92		

Private Tertiary sector					
Primary energy savings in Industry sector	MTOE/year	2.28	7.14		
Primary energy savings in Transport sector	MTOE/year	1.71	6.05		
Reduction in final energy consumption as result of obligatory energy efficiency systems	%/ year		-1.5 (without transport sector)	9.18% (compared to 2017 or 2019)	-0.8 (without transport sector)
	MTOE/year		10		
Final energy savings in the residential sector	MTOE/year	3.09	3.67		
Final energy savings in the public tertiary sector	MTOE/year	0.19	0.57		
Final energy savings in the private	MTOE/year		0.66		

tertiary sector					
Final energy savings in the industry sector	MTOE/year	1.95	5.1		
Final energy savings in the transport sector	MTOE/year	1.18	5.5		
Share of RE in the gross final energy consumption	**%**	**18.3**	**17**		**28 ~ 30**
RE heating and cooling	%/ year				+1.3 (indicative)
	%				30 ~ 33.9
RE Electricity	%				55
RE Transport	%		10		21 ~ 22

2.5.3. EE and RE technology options

Unfortunately, the updated plan (NECP 2019) as well as the SEN 2017 did not provide detailed actions on how the 2030 targets will be technologically achieved. There are no clear objectives for the energy mix by 2030, however, it is expected that the electricity generation technology mix will change to meet the requirement of RE and EE targets set out in the Italian energy climate policy and the Fit for 55 package.

First, coal and nuclear-based technologies will not be considered in future scenarios. The first will not be promoted due to the need to reduce GHG emissions, and the latter has never been exploited in Italy.

Second, renewables such as biofuels, solar and wind will be developed. For electricity generation, solar will be the most potential technology given its technological and economic feasibility. Meanwhile, biofuels will mainly be used for transportation and partly for electricity generation.

Third, the share of natural gas is currently high which in the short term is expected to remain stable (at least). In case the increases in solar, wind and biofuels do not meet the electricity demand, natural gas will be utilized.

Forth, imported electricity will be stable or increase. The case of imported electricity is similar to that of natural gas, in which electricity will be imported in case of domestic renewables do not meet the electricity demand. However, the binding commitment to GHG emission reduction will promote imported renewable sources. In other words, Italy will need to seek renewable electricity exporting countries, probably in the Balkans and North Africa.

Fifth, energy efficiency measures are encouraged in industry, agriculture, household and service, etc.

In 2021, before the introduction of FIT for 55, Terna and Snam developed the energy scenarios called National Trend Italia (NT Italia) for the horizon years 2025, 2030 and 2040, using modelling tools for electricity demand, gas demand and market simulation (Snam and Terna, 2021).

In these scenarios, there are several points which are similar or updated from the previous strategies, including:

Electricity production from renewable sources of NT Italia is consistent with the NECP, although the details on each type of renewable sources have been adjusted, overall the total production of the two scenarios is similar.

Import-export balance in NT Italia is higher than that of NECP. This is due to the use of market simulation on the entire EU and an update of the Italian grid. The increase in net imports, with the same needs and renewable generation, entails a reduction in expected thermoelectric production, especially for the reference year 2030 (118 TWh in the NECP, 100 TWh in the NT Italia.

Gas consumption for electricity generation is similar to that of NECP, although the overall gas thermal electricity generation is lower in NT Italia. This is due to the technological improvement considered in NT Italia, which is closer to reality than the previous scenarios of NECP. Moreover, it can be argued that the consumption of gas will be accompanied by the development of green gases such as biomethane and renewable hydrogen.

Specifically, the forecasted installed capacities and generations of the Italian electricity grid of NT Italia are presented in Table 9.

Table 9. Scenarios of electricity development by 2025, 2030 and 2040

	2025	2030	2040
Electricity generation (TWh)	**326**	**331**	**381**
Gas	137	95	103
Coal and other non-RE	8	5	3
Solar (with CSP)	39	70	87
Wind	30	40	71
Hydropower	49	49	55
Other RE	23	23	26
Net import/ export	43	58	53
Loss (perdite accumuli)	-1	-4	-5
Curtailment	-1	-5	-12
Installed capacity (GW)	**120**	**144**	**164**
Gas	49	48	48
Coal and other non-RE	2	2	2

Solar (with CSP)	29	52	64
Wind	16	19	25
Hydropower	19	19	20
Other RE	4	5	5

As shown in Table 9, the installed capacity of gas thermal power will be stable at 48 GW; however, the electricity generation will fluctuate and reach 103 TWh by 2040. Between 2030 and 2040, the fuel of some plants will be converted from natural gas to green gas.

Coal will be phased out in 2025, and there will be a conversion of coal into other fuel plants with lower specific emissions. There will be only about 1 GW of the coal power plant in Sardinia, until the Tyrrhenian Link will be put into operation to guarantee the safety of the electricity system. The total combination of coal and other non-renewable electricity will be stable at 2 GW till 2040, being equivalent to about 3 TWh of electricity.

Between 2025 and 2040, there will be a constant growth in renewable electricity, reaching 64 GW for solar and 25 GW for wind (including 4.2 GW offshore) by 2040. The electricity generation from solar and wind will increase accordingly, at 87 and 71 TWh of solar and wind power by 2040, respectively. The installed capacity and electricity generation of hydro and other renewables will be stable, at 55 TWh of hydropower and 26 TWh of other renewable electricity by 2040.

In the same period, the net import and export will also increase. In 2019, the net import export of electricity between Italy and neighbouring countries was 38.2 TWh. By 2025, this number will mount to 42.8 TWh due to the phase-out of coal in Italy, and the (still) presence of nuclear power in France, competitive lignite and coal plant in Germany and in the Balkan area. In the years 2030 and 2040 a significant increase in imports is observed (72 TWh in 2030 and 73 TWh in 2040 vs 53.7 TWh in 2025) there is also an increase in export trade (14 TWh by 2030 and 20.1 TWh by 2040 vs 10.9 TWh in 2025), which will lead to a constant increase in the energy exchanged in both directions on the border. Table 10 presents the electricity import and export between Italy and neighbouring countries.

Table 10. Plan for electricity import and export by 2025, 2030 and 2040

Import/ Export of electricity (TWh)		**2025**	**2030**	**2040**
France	Import	27.8	29.2	30.3
	Export	2.9	1.9	2.4
Switzerland	Import	13.3	22.9	28.8
	Export	2.8	2	1.9
Austria	Import	2.6	6.7	6.9
	Export	1.1	1.1	1.2
Slovakia	Import	3.3	4.2	3
	Export	1.1	0.5	1.4
Monaco	Import	4.3	4.4	2.0
	Export	0.3	0.3	2.4
Germany	Import	2.5	4.6	1.7
	Export	1.0	1.8	5.4
Malta	Import	0.0	0.0	0.2
	Export	1.7	1.6	0.9
Tunisia	Import	0.0	0.0	0.0
	Export	0.0	4.6	4.5
Total	Import	53.7	72.0	71.6
	Export	10.9	13.7	18.6
	Net import/ export balance	42.8	58.3	53.0
	Net exchange	64.6	85.7	90.2

Recently, due to the impacts of the war in Ukraine, there are some changes in the national policy to adapt to the increasing price and shortage of supply of energy in general and natural gas in particular, as well as to release the dependency on foreign supply of energy. This change aims at maximizing the production of electricity from fuels other than natural gas (coal and bioliquids). Specifically, the energy sources for electricity generation are going to be more diverse, with the contribution of RE (MITE, 2022).

From the 1st August 2022 to 31 March 2023, the maximum operation of coal and oil existing plants contribute to a reduction of about 1.8 billion m^3 of natural gas. Together with other activities in existing plants generating electricity from bioliquids (reducing operating hours) and diesel (temporary authorization of operation), the total natural gas saving is 2.1 billion m^3 (MITE, 2022).

CHAPTER 3. LITERATURE REVIEW ON RESEARCH METHODOLOGY

This chapter describes the state of the art on consequential life cycle assessment in the energy sector in general and the power sector in particular. It includes the description of the methodology, with focus on the combination of economic and environmental models for performing C-LCA in the power sector. This chapter will answer the third research question: What are the methods and the approach for quantifying and evaluating life cycle environmental impacts as consequences of changes?

This chapter clarifies the limits in the available methodology applied in research community for quantifying and evaluating life cycle impacts as consequences of changes. These are the foundations for proposing a detail framework for conducting the study, which will be described in the next chapter.

3.1. Consequential life cycle assessment - Concepts

Life cycle assessment (LCA) quantifies the life cycle environmental impacts of a product system, covering all stages, including raw material extraction and processing; product/ service manufacturing, use and disposal; and transportation (Horne, 2009). The comprehensiveness makes LCA a particularly effective mechanism for quantifying different environmental impacts originating from the product's life cycle including indirect impacts.

There are two types of LCA approaches, namely attributional LCA (ALCA) and consequential LCA (C-LCA). In the ALCA approach, inputs and outputs of a product system are attributed to its functional unit by linking the unit processes of the system while defining a physical boundary and isolating it from other systems (Bjørn et al., 2018). ALCA quantifies the physical inflows and outflows directly related to the product system, without considering the effects that it can generate on other economic sectors.

Meanwhile, C-LCA has been developed to quantify the environmental impacts of a product system in relation with changes within its life cycle (Bjørn et al., 2018). It expands the system boundaries by including the marginal or avoided impacts induced by a change in the product system on other economic sectors. The product system can be considered as a 'partial process' that overlaps and influences other processes (Georgescu-Roegen, 1971). New spatial and temporal boundaries of the product system must be defined in C-LCA, according to the goal of the analysis.

To make a clear distinction between C-LCA and ALCA, several authors conducted systematic reviews on C-LCA methodology (Earles and Halog, 2011; Roos and Ahlgren, 2018; Soimakallio et al., 2011). Other authors reviewed different models for life cycle analysis and focused on the outstanding features of C-LCA in capturing environmental impacts of a product system under economic interactions (Marvuglia et al., 2013; Sanchez et al., 2012; Zamagni et al., 2012). These reviews indicated that ALCA and C-LCA are vastly different in terms of application scale for small/large economic sector, (increased) number of products, (expansion of) system boundary. The differences between C-LCA and ALCA are summarized in Table 11.

Table 11 . Comparison between ALCA and C-LCA (Soimakallio et al., 2011; Zamagni et al., 2012)

Features	ALCA	C-LCA
Goal	To assess potential environmental impacts, including inputs and outputs of a product system per its functional unit over its life cycle.	To assess potential environmental impacts of a product system in relation with changes per its functional unit over its life cycle.
Application	Answer for question 'How things are?' Hotspot identification or product comparison. ALCA is relevant when no specific decision is at hand for increasing the understanding of the causal relations within the product chain, and between this chain and the surrounding technological systems.	Answer for question 'What if?' Reflection of causality. Used for decision making. C-LCA is relevant when rational decision making is needed. This process requires information about the consequences of the decision.
Product system	Normally there is one product system per a LCA.	The product systems are broadened to include several similar or relevant products.
System boundary	Over the product system's whole life cycle (from cradle to grave), or a part of its life cycle (from cradle to gate, from gate to gate, from gate to grave).	The system boundary is broadened to include unit processes and products as consequences of change/ intervention.
Functional unit	1 unit of function of product system.	1 unit of function of marginal product system. Functional unit of the whole system would consist of multiple functions, including the main system and those added by the processes included in the boundaries.

Allocation	The impacts are ascribed for main product and co-products based on economic value (price) or physical value (volume, mass).	System boundary is broadened to include main product and co-products, so there is no need of allocation.

3.1.1. *Direct vs. indirect environmental impacts*

The life cycle environmental impacts of power system, especially renewable power technologies have been widely studied. For example, Góralczyk assessed the life cycle environmental impacts of RE at global scale for the whole energy industry (Góralczyk, 2003), or Balcombe et al. and Fthenakis et al. studied those of RE technologies (Balcombe et al., 2005, Fthenakis et al., 2008 cited in (Jones and Gilbert, 2018)). Liu et al. studied the environmental impacts of new energy technologies over its whole life cycle (Liu et al., 2012).

The life cycle environmental impacts include not only direct impacts arising during the generation of power, but also the indirect ones. The indirect impacts may lie in the intermediate products that contribute to the power's life cycle, e.g. land use impacts for the development of bio-electricity, impacts from equipment and power infrastructure, impacts from background processes such as primary energy, fuel extraction for power generation. Moreover, they may be originated from the affected products which are related to the power in some ways, e.g. impacts from increasing battery integration into the power grid on other types of power technologies such as wind power, solar power or thermal power in the generation mix, impacts from increasing or decreasing demand on products of power intensive industries such as metal manufacturing and food processing on power grid structure and capacity.

While the former type of indirect impacts (e.g., impacts from intermediate products) can be quantified with ALCA as can be seen in the studies of Góralczyk, 2003, Balcombe et al., 2005, Fthenakis et al., 2008, Liu et al. 2012; the latter types of indirect impacts (e.g., impacts from affected products) should be quantified with C-LCA. In this thesis, the term 'indirect environmental impacts' is used to denote the latter type of impacts which originates as the consequence of changes in the product system. These changes include different types of changes in the socio-economy such as changes in the governmental policy decision, or changes in the market demand of the studied product system or any relevant products and co-products.

The comparison of literatures is complex because there are differences in methods (geographic coverage, temporal horizon, system boundary, applied economic modelling tools and assumptions) and product systems' characteristics (different types of electric power, grid inclusion or exclusion), etc. Therefore, this chapter briefly reviewed C-LCA in energy and power sector in terms of applied methods, subsequently focused on the ability of C-LCA in obtaining results on the direct and indirect environmental impacts of power system.

3.1.2. *Economic causal relationship*

Originally, C-LCA was defined as aiming ‘at describing the effects of changes within the life cycle’ (Ekvall, 2002). Similarly, other authors defined C-LCA as ‘an approach describing how the environmentally relevant physical flows to and from the technological system will change in response to possible changes in the life cycle’ (Ekvall and Weidema, 2004) or ‘an approach to estimate how flows to and from the environment will change as a result of different potential decisions’ (Curran et al., 2005). Soimakallio et al., who agreed with (Ekvall, 2002), defined C-LCA as a method for describing potential changes in environmental impacts of a product system in response to possible decisions that would have been or will be made (Soimakallio et al., 2011).

These definitions focus on the causal relationship of C-LCA approach which occurs during different processes over the product system’s life cycle. The two distinguished features of C-LCA were pointed out: (1) changes in the environmentally physical flows and (2) as consequences of changes in the life cycle of the product system (Curran et al., 2005; Ekvall, 2002; Ekvall and Weidema, 2004; Soimakallio et al., 2011). These changes (effects) occur in the technological (product) system, while the cause of changes originates from different decisions. These decisions occur during the life cycle of the product system. There is no limitation on types of decisions, and it may extend to decisions on technological improvement of a company, or governmental policy decisions on subsidy for a product, or to limit the consumption of a product.

Some authors extended the definition of C-LCA to include the environmental impacts on other sectors due to market related changes, that is an increase or decrease in demand on the product system. For example, Nielsen et al. assessed the environmental impacts of the product system in which ‘environmental profiles are compiled by addressing changes induced by a change in demand for the company’s products’ (Nielsen et al., 2007). Earles and Halog defined C-LCA as ‘an emerged modelling approach for capturing environmental impacts of product systems beyond physical relationships accounted for in ALCA’ (Earles and Halog, 2011). In other words, the common principle of causal relationship of C-LCA was handled under the view of economic interactions.

Earlier, Georgescu-Rogen mentioned the solution for including impacts of economic activities and the energy- material flows by consider the energy sector under a set of economic processes instead of a thermodynamic flow (Georgescu-Roegen, 1986) and proposed the passing to the multi process matrix to better cover several socio-economic indicators which are unavailable in the input-output matrix (Georgescu-Roegen, 1979).

The economic relations between the studied product system and other economic sectors, therefore, will cause indirect environmental impacts due to a change in the studied product system on other relevant product systems and vice versa. As an example: the EU bioenergy policy requires the bioethanol consumption by 2030, which causes an increasing demand of this product system in the same timeframe. In order to meet that demand, bioethanol exporters to EU market, e.g. from Malaysia, have to produce more bioethanol. This will require more inputs (land, seeds, fertilizers, etc.) in Malaysia to grow energy crops. At the same time, the amount of co-products of the bioethanol production process, e.g. animal feeds, will increase. As a consequence, the environmental impacts of bioethanol product system will now equal to direct impacts of bioethanol, adding indirect impacts from increased bioenergy production in Malaysia, subtracting indirect impacts from reduced animal feeds being substituted by Malaysian animal feeds.

On practice, the coupling of environmental and economic metrics has been studied for a long time. It started with the effort of linking between demand on energy sources and an economic activity (Brown and Herendeen, 1996). The consumed resources were various in terms of natural resources such as copper in Leontief cited in (Brown and Herendeen, 1996), nitrogen in Herendeen cited in (Brown and Herendeen, 1996) or social resources such as labour in Bezdel and Hannon cited in (Brown and Herendeen, 1996). These resources were initially focused on their embodied energy (Brown and Herendeen, 1996) and were later broadened into energy and material, for example Raw Materials Equivalents tools and database of Eurostat (Schoer, 2019), System of Environmental Economic Accounting database of the United Nations (UNSD and UNCEEA, n.d). This coupling quantified the energy and material used for the product or service itself, as well as those used in the background processes during the production of that product or service.

However, there are risks on mixing different approaches based on physical valuation, e.g. energy analysis, material flow analysis, and economic valuation, for example double counting (Georgescu-Roegen, 1975), combination of different metrics (Georgescu-Roegen, 1975) and uncertainty due to transformation of energy (Brown and Herendeen, 1996). The proposed solution for this analysis was to use a process-based matrix which composed of both economic and physical inputs and outputs (Georgescu-Roegen, 1975). In other words, it is the transformation of pure economic input-output methodology or pure (physical) energy and material analysis methodology to get the best of both worlds.

At the same time, C-LCA is usually based on a quantitative analysis, and this can represent a limit of the methodology, considering that economic growth involves not only quantitative changes but also qualitative transformations, as suggested by Georgescu-Roegen (Georgescu-Roegen, 1975). This aspect should be further integrated in future C-LCA studies or in any case, a trade-off between C-LCA outcomes and other qualitative aspects should be integrated in multi attribute decision making processes.

3.1.3. Market boundary

One of distinguished features of C-LCA is the expansion of system boundary; that is, the inclusion of unit processes (Zamagni et al., 2012) and different products and co-products (Weidema, 2003) to the extent of the expected changes. At the early time of C-LCA development, Weidema proposed an approach, in which the expansion of system boundary was conducted under the ceteris paribus (other things being equal) assumption (Weidema et al., 1999). The author suggested an approach to identify affected products in five steps (Weidema et al., 2009, 1999), including:

(1) What scale and time horizon does the study apply to?

(2) Does the change only affect specific processes or a market?

(3) What is the trend in the volume of the affected market?

(4) Is there potential to provide an increase or reduction in supply and demand?

(5) Is the technology the most/least preferred?

This stepwise approach clarified the links between the product systems and unit processes through intermediate products (ALCA) as well as identified the consequences on supply and demand of products and co-products (C-LCA) (Weidema et al., 2009). Due to the limitation of data availability at that time, the scale of change was assumed to be small (Weidema et al., 2009). Therefore, the suggestion of applying the ceteris paribus assumption when expanding the system boundary is reasonable.

Frischknecht and Stucki proposed a methodology framework in which different modelling techniques will be applied depending on the changing agent, its potential effect and the size of studied product systems (Frischknecht and Stucki, 2010). Specifically, if the changing agent has small potential consequences (e.g., individual decision of buying lamps of company X), the ceteris paribus assumption should be applied. Meanwhile, if the changing agent has large potential consequences (e.g., policy to encourage the consumption of five-star energy rating lamps in country Y), the mutatis mutandis ('the necessary changes being made') assumption should be applied (Frischknecht and Stucki, 2010).

In the former example, the decision of whether to buy a specific product is applicable at a small scale, and the consequence of that decision is limited in physical changes; that is, changes of quantity of environmental impacts without changes in economic systems. Meanwhile, in the latter example, the decision of introducing a policy to encourage a product or technology will induce changes in other relevant economic sectors. In order to accurately quantify the impact, it is necessary to expand the system boundary. Frischknecht and Stucki concluded that C-LCA, therefore, would be relevant for quantifying impacts of changes due to governmental policy or strategic international organization decision in which the investigated object has a relatively large economic size (Frischknecht and Stucki, 2010).

It is suggested that if the relative economic size of studied product system is small to medium, i.e. accounting for less than 0.1% or from 0.1% to 1% of the market share, respectively, the ALCA approach should be applied. In contrast, if the market share of the studied product system is larger than 1%, the C-LCA approach should be applied (Frischknecht and Stucki, 2010). Although the criteria are not adequately convincing, they are the initial efforts of how to deal with system expansion in C-LCA, based on quantitative economic value.

The system boundary is extended to at least two products in all reviewed studies. Moreover, it is even extended to several relevant economic sectors. The investigated products and economic sectors of some reviewed C-LCA papers are specified in Table 12.

Table 12 . Product systems and affected products of some reviewed papers

Studies	Investigated product systems	Affected products	Coverage of economic sectors
Pizarro-Alonso et al. (Pizarro-Alonso et al., 2018)	Waste management approaches, waste to energy	Different types of power such as coal, natural gas, biomass, wind, solar, ocean, geothermal and nuclear power	Two sectors of waste management and power generation
Moora and Lahtvee (Moora and Lahtvee, 2009)	Waste management approaches	Different types of power	Two sectors of waste management and power generation
Pehnt et al. (Pehnt et al., 2008)	Wind power	Thermal power such as power from coal, lignite and gas	
Blanco et al. (Blanco et al., 2020)	Power to methane	The EU power system	The whole economic system of energy supply and demand sectors, including power, heat, industry, transport, and supply (supply); and commercial, residential, industry, mobility and agriculture (demand)
Mathiesen et al. (Mathiesen et al., 2009)	Power and heat from waste	Energy from coal, oil, natural gas and biomass	
Lund et al. (Lund et al., 2010)	Power	Energy from wind, coal and natural gas	

Igos et al. (Igos et al., 2015)	Six energy final products including liquid fuels, fuels, coke, refined petroleum, electricity, products of mining and quarrying of energy, and gas, steam and hot water		Six economic sectors of Luxembourg: Agriculture, Construction, Industry, Electricity production and distribution, Transport, and Other industries
Gibon et al. (Gibon et al., 2017)	17 energy technologies including bioenergy, coal, hydropower, natural gas, natural gas, concentrating solar power, nuclear power, solar photovoltaics (solar PV), wind power and CCS		
McDowall et al. (McDowall et al., 2018)	18 power technologies from wind, solar PV, coal, combined cycle gas turbine, conventional gas, nuclear, hydro, oil, biomass and waste		The comprehensive energy supply and demand sectors of fuel provision sectors, power generation sectors (Agriculture, Forestry, Coal, Leather, Wood, Pulp & Paper, Printing & Media, Coke, Nuclear fuel, Chemicals, Rubber & Plastic products, Other non-metallic mineral products, Fabricated metal products) and power consumption sectors (Agriculture, Pulp & Paper, Chemicals, Non-Metallic minerals and Other industry)
Raugei et al. (Raugei et al., 2018)	Solar PV power	Different types of UK on-grid power such as wind, nuclear, coal, gas and biomass power	
Algunaibet et al. (Algunaibet et al., 2019)	The US power system with power from coal, natural gas, nuclear, hydropower, biomass, geothermal,		

	solar PV, solar thermal, wind, bioenergy and CCS		
Vandepaer et al. (Vandepaer et al., 2019a)	Two types of batteries	On-grid power	
Dandres et al. (Dandres et al., 2017)	The European (EU) electricity and heat		20 globally economic sectors: Grains and crops; Livestock and meat products; Processed food; Water; Textiles and clothing; Light manufacturing; Heavy manufacturing; Utilities and construction; Transport and communication; Other services; Coal and lignite extraction; Gas extraction; Oil and peat extraction; Minerals; Fuels; Gas, steam and hot water; Electricity; Forestry; and Pulp, paper, publishing and Wood products
Elzein et al. (Elzein et al., 2019)	France grid power with different price and generation technologies	Normandy grid	

All of the reviewed studies expanded the product system boundary by either increasing unit processes or including relevant products and co-products. This approach helps to identify products or technologies being affected as consequences of changes. However, the ways how these affected products and co-products being treated were different. Some authors treated the affected product under ceteris paribus assumption. In this case, they simulated the consequences in the form of physical changes, or the affected products can be substituted by other similar ones. These physical changes were modelled through quantifying energy flows; for example in Jones et al.'s study which used net energy analysis (Jones et al., 2017). The affected products were treated by substitution and cut-off; for example, the marginal electricity production was replaced by the power from waste incineration and material recycling as in Eriksson et al.'s study (Eriksson et al., 2007).

The reviewed papers that applied the ceteris paribus assumption were conducted at the early time of C-LCA development, when the methodology was emerging. At that time, most authors focused on the causal relations of change in the product system and affected product rather than socio-economic relations between them. These 'claimed to be C-LCA' studies should be regarded as using consequential concept, in which they applied consequential approach by mentioning the causal relationship and its consequences on the environmental impacts of the product system without considering it under the socio-economic interactions.

Another approach to identify affected products is considering them under the mutatis mutandis assumption. The changes in the affected products were determined by reviewing literatures, seeking for stakeholders' participations, and running economic models. In power sector, Mathiesen et al. identified marginal energy technologies by looking at publications on historical and future energy system and existing C-LCAs (Mathiesen et al., 2009); Dandres et al. took the business-as-usual (BAU) and future renewable technology mixes from peer-reviewed publications (Dandres et al., 2011); and Gibon et al. determined the existing power generation mixes and the regional technology performance from International Energy Agency reports and the New Energy Externalities Development for Sustainability project, and identified changes in the future power system structure and fuel consumption due to the increased adoption of clean power technology based on experts' opinions (Gibon et al., 2017).

Several authors used economic models to determine marginal technologies such as EU Electricity Market Model (E2M2) (Pehnt et al., 2008), EnergyPLAN (Lund et al., 2010; Mathiesen et al., 2009), MARKAL (Choi et al., 2012), ETEM (Igos et al., 2015), Energy2020 (Dandres et al., 2017), Network Impact Assessment Model (Jones and Gilbert, 2018), TIMES (ETM-UCL) (McDowall et al., 2018), Unit commitment model

(Raugei et al., 2018), Balmorel (Pizarro-Alonso et al., 2018), Swiss TIMES Energy Model (STEM) (Vandepaer et al., 2019a) and JRC-EU-TIMES (Blanco et al., 2020).

The changes in product system and its environmental impacts may occur within its own boundary. These changes may be physical changes of the product system, for example, change in the carbon stock of land used for bioenergy will induce change in bioenergy GHG emission. Other examples such as change in the solar radiation (nature) or wind generator efficiency (equipment), which will induce change in the output of the renewable energy systems, consequently change the environmental impacts of the systems. At this point, the consequential approach quantifies the environmental impacts by taking the absolute value of the impacts of the studied product system after and before change, without the need to consider the product system under the linkage with other economic sectors.

It should be noted that this concept does not ignore at all the circularity effect of conventional LCA, in which (partial) outputs of one process are inputs for others. A simple example as followings: to generate fossil fuel-based power, we need minerals or fuels such as coal or natural gas. In turn, we need power (energy) to mine coal or to exploit natural gas. This creates a loop of physical inputs and outputs over the product system's life cycle. On one hand, this loop results in a circulation of energy and material inside the product system boundary, and at the end of the day, it raises a question of net energy and material output (Georgescu-Roegen, 1975). On the other hand, we must not forget the role of other inputs contributing to a product system other than environmentally physical ones. These include socio-economic inputs such as capital and labour (Georgescu-Roegen, 1975). As a consequence, it returns to the importance of identifying the system boundary of a C-LCA (Georgescu-Roegen, 1971).

When being considered under the economic interactions, the system boundary of C-LCA, goes beyond the physical boundary to extend to the market boundary. The physical boundary of the product system, as being widely accepted, covers a spatial, geographical dimension, for example, a region or country during four stages of a product life cycle: raw material extraction, manufacturing, using and end of life. Meanwhile, the market boundary covers a market area of several industries and economic sectors. It also considers market effects; for example, changes in electricity price and production cost, and sometimes even consider rebound effect and feedback mechanism.

In any case, still now the establishment of the boundary is one of the most debated questions of C-LCA. However, including or excluding some processes is sometimes done inconsistently, using different arguments, which leads to different results.

3.1.4. Socio-economic interactions

According to Weidema, Earles and Halog, Zamagni et al., while ALCA focuses on the physical inflows and outflows of environmental impacts of a product system, C-LCA considers the interactions of economic sectors[10] on the product systems and the relevant environmental impacts (Earles and Halog, 2011; Weidema, 2003; Zamagni et al., 2012). These authors agreed on the economic interactions in the C-LCA through the inclusion of market mechanism or economic-based causal relationship.

The most common way to model the economic relationship is combining an economic modelling tool and LCA. The applicable economic models are either partial equilibrium model (PEM), general equilibrium (GE), input output (IO) or dynamic models (DM), which are also common in C-LCA studies in energy sector in general (L. Q. Luu et al., 2020). Two thirds of reviewed papers applied economic models to simulate the economic interactions between the power sector and other sectors. The pathway for integrating these models into C-LCA is running the models to obtain scenarios with changes in affected sectors and identify affected products/ technologies. These scenarios and data on affected products/ technologies will be used for running C-LCA.

The good point of integrating economic models, e.g. IO/ PEM/ GE into LCA, is that they can provide details of the economic causal relationship (Beaussier et al., 2019). Economic models work with one or several economic sectors; therefore, they either provide a specific view of one economic sector, or a comprehensive view of the product system in relations with the economy. This will help to clearly identify the hot spot economic sectors that contribute most to the impacts. Different economic modelling tools for conducting C-LCA will be analysed in the section 'Economic models for ' of this Chapter.

The economic model based C-LCA accurately tracks the links between environmental impacts and economic indicators. Dandres et al. applied GE model to predict global economic perturbation potentially caused by two different European energy policies, and C-LCA to quantify environmental impacts due to these policies. It was identified that, among economic sectors, the most impacted sectors were the coal extraction and power generation ones. Consequently, it contributes to most of the difference in the environmental impacts across the two scenarios. Moreover, the authors pointed out that the most sensitive causal relation lied in economic revolution or the change

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[10] The term 'economic sectors' denotes System of National Accounts economic (production) sectors, which are described in monetary and economic flows UNSTATS 2009. The System of National Accounts (SNA). European Communities, International Monetary Fund, Organisation for Economic Co-operation and Development, United Nations and World Bank. New York..

in the GDP, rather than the change in the demand (Dandres et al., 2011). Similarly, Igos et al. applied PEM and GE models to evaluate the economic impacts of policy decisions on energy commodity demand in Luxembourg by 2030 and identify the least cost technologies to meet that energy demand. The authors identified that the contribution of other economic sectors, except for energy sector, are quite similar across studied scenarios. Moreover, most of the environmental impacts originate from imported commodities (Igos et al., 2015).

Apart from economic causal relationship, C-LCA also covers the social interrelations among the product system. In this case, the original changes are not limited to the decrease or increase of consumption and production which are quantitative, but also include changes in social indicators. This is mostly conducted with the application of DM such as system dynamics and agent based modelling.

C-LCA based on system dynamics was applied to model sustainability impacts of three alternative vehicles including internal hybrid, plug-in hybrid and battery EV by 2050 and compared them with internal combustion vehicle (Onat et al., 2016). The increase in the number of EVs being used caused environmental, economic and social impacts on carbon dioxide emissions, particulate matter formation, photochemical oxidant formation, vehicle ownership cost, contribution to GDP, employment generation, and the human health impacts. With C-LCA approach, it was identified that EVs were expected to be the best alternative in long-term for reducing human health impacts and air pollution from transportation. Meanwhile, the result based on average value indicated that plug-in hybrid vehicles had the largest potential GHG emission reductions (Onat et al., 2016).

Florent and Enrico combined agent based modelling and C-LCA to model changes in vehicle private use in Luxembourg in relation with environmental impacts of battery EVs, plug-in hybrid EVs by 2020, and compared them with gasoline internal combustion vehicles and diesel internal combustion vehicles (Florent and Enrico, 2015). Different mobility policies cause changes on characteristics and number of travels, charging patterns and auxiliary use, consequently decrease global warming, fossil depletion, acidification, ozone depletion and photochemical ozone formation; and increase in metal depletion, ionizing radiations, marine eutrophication and particulate matter formation (Florent and Enrico, 2015).

In 2017, Frischknecht et al. has reviewed papers of the 62nd LCA forum, and indicated that C-LCA goes beyond the marginal mixed and avoided burdens (Frischknecht et al., 2017). It involves causal modelling, which not only includes economic relationship but also social responsibility (Weidema, 2016 cited in (Frischknecht et al., 2017). Although the social responsibility referred by Weidema concerned on the consequences of a company's action, it could be extended to the context of governmental policy intervention. An example is the impact on social wellbeing and rate of employment/unemployment, specifically the decreased labour in coal mining industry and the increased labour in solar PV panel manufacturing, due to the policy on renewable portfolio standard. In this case, the impacts of policy intervention would be larger than those of a company decision.

Among the reviewed papers there were only two case studies covering the social aspects or social relationship of the power system. These studies either simulated the social agents and their impacts on the product system (Florent and Enrico, 2015), or simulate the socio-economic interactions of the product system over its life cycle (Onat et al., 2016).

Although there were not many C-LCA studies on the power sector considering the social interactions at present, with the call for social inclusion in LCA community and the consequential impacts of increasing the integration of renewable energy sources into the power system, it is expected that there will be more need of C-LCA methodology to work with socio-economic indicators in analysing and assessing impacts of power system in the context of GHG policy intervention.

3.1.5. Some concluding remarks of the C-LCA methodology

By expansion of system boundary and inclusion of socio-economic interactions, C-LCA shows its strength in quantifying indirect life cycle environmental impacts of power sector. Consequently, it is more suitable in analysing and assessing life cycle impacts of power sector compared to ALCA in the context of energy and environmental policy aiming at GHG emission reductions.

The expansion of system boundary is observed in all reviewed papers by inclusion of unit processes, affected products and co-products, and economic sectors to the extent of changes. Although the affected products are treated differently among reviewed papers, it should be noted that the selected assumption, either ceteris paribus or mutatis mutandis, largely depends on the availability of data and the economic size of investigated product systems. With the expansion of system boundary, C-LCA covers a larger number of affected products, and relevant unit processes, economic sectors. As a result, it would comprehensively quantify the environmental impacts which may be neglected in ALCA.

The inclusion of socio-economic indicators in a C-LCA is frequently conducted by applying an economic modelling tool. The application of economic models and C-LCA has the advantages of tracking the links between environmental impacts and socio-economic indicators, such as product demands or economic growth, domestic market or import/export market, and consumer behaviours. Therefore, C-LCA would have an upgraded advantage of hotspot identification compared to ALCA.

In this thesis, I follow the notion of C-LCA in which

> ***The environmental profile of the product system includes both direct and indirect impacts, originating from the change in the product system life cycle, while interacting with other aspects of the economy and society***.

This can only be done by ***expanding the product's physical system boundary*** and ***considering the product system under the socio-economic interactions***.

3.2. Application of C-LCA in energy and power sectors

The practical application of C-LCA in the energy and power sectors was analysed and reviewed through 102 research papers being published before 2020. The literature search was conducted on Web of Science with the terms of 'consequential life cycle assessment AND energy sector' in January and February, 2020. The term 'energy' has been selected instead of 'power' because it was assumed that there were studies on energy sector which included power, heat, fossil fuels, and biofuel. The initial search gave out 221 C-LCA papers being published from 2005 to the present.

These 221 papers were primarily screened through the titles and abstracts to exclude ones relevant to food/nutrient energy and ones that assessing energy as a medium during the production line, instead of the product system. At the end of this primary screening, there were 118 papers conducting an C-LCA in energy sector, including reviews, papers proposing framework/ approach and papers with illustrated case study. Of which, there were 102 papers with illustrated case studies.

Research on C-LCA was scatterly conducted before 2010. The number of papers increased steadily since 2011 and was at peak in 2017. The numbers of papers by year and topic are presented in Figure 10.

The literatures mainly focused on three topics: bioenergy, power and other. Papers on 'bioenergy' topic accounted for 56% of the total number of papers. This may be originated from the interrelation of bioenergy and other sectors such as agriculture in terms of land use change and transportation in terms of globally scaled geographical lines of biofuels, and social controversy between 1st and 2nd generation of biofuels.

Papers on 'power' topic were composed of those studying different types of electric power, i.e. coal, natural gas thermal power, nuclear power, hydropower, renewable power, fossil fuel-based power with carbon capture and storage (CCS). It also included papers studying both power and heat simultaneously (including power as one of the product systems or using power as the only input during the product system useful life) and electric vehicles (EV) which have recently entered as the power system for regulation purposes through Vehicle To Grid (V2G) initiatives. The number of studies on the 'power' topic was very little in the first half of the research period, but has recently increased, with six papers in 2019. This can be explained by the change in the power system, with the integration of such renewable power as wind and solar, and consequently energy storage systems, which requires the need of a C-LCA approach to model environmental impacts in relation with power system changes. There were 31 case study papers of C-LCA on power sector at total.

Papers on topics of 'other' account for a small number of total papers (20 papers). These cover different product systems such as fuel cell bus, hydrogen, heat (only), fossil fuels.

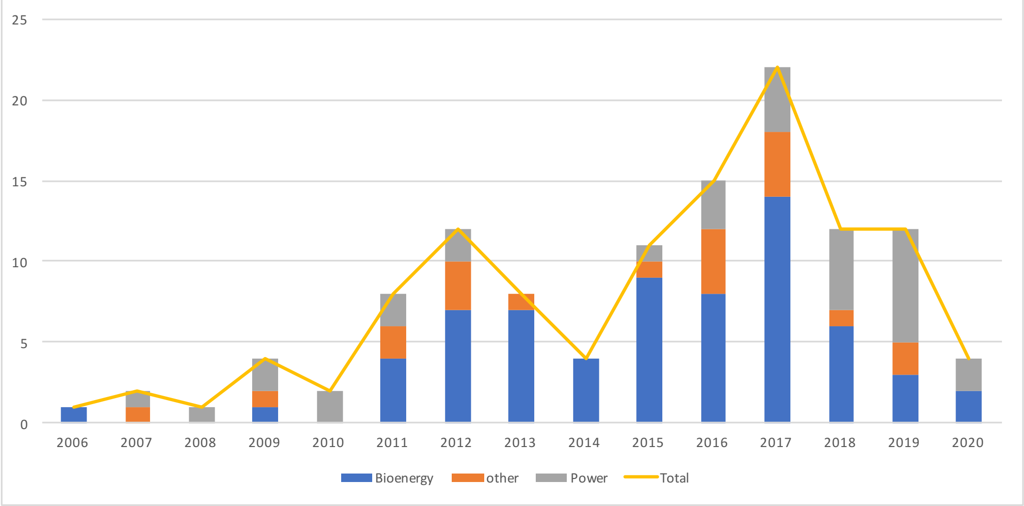


Figure 10 . Numbers of articles by years and topics

3.2.1. *Geographical coverage*

There is a large difference in geographical coverage of C-LCA studies. 74 out of 102 the case studies are conducted within EU and UK boundary, up to 73% of studies. Meanwhile, only a small number of studies conducted elsewhere around the world, in Asia (11), America (8), Australia and New Zealand (2) and Africa (1). Interestingly, there are five studies conducted at global scale, which try to identify the global marginal energy mix, for example global nuclear power development (Warner and Heath, 2012), global electric mix (Herbert et al., 2016), global low carbon electricity (Gibon et al., 2017), global biofuel transport (Some et al., 2018) and long term marginal electricity mix of 40 countries (Vandepaer et al., 2019b).

3.2.2. *Temporal horizon*

In term of temporal horizon, two papers (Hou et al., 2017; Moore et al., 2017) out of 102 case studies modelled the change in the past through survey and monitoring program. Specifically, Hou et al. conducted a monitoring project and a questionnaire survey on biogas consumption and leakage and digestate quantities for the two villages in China (Hou et al., 2017). Data in the study were obtained in 2010 to calculate the GHG balance and in 2014 to evaluate changes in rural household biogas system (Hou et al., 2017). Meanwhile, Moore et al. carried an analysis of various scenarios with two control variables: crop management techniques and source of nutrients for sugarcane crops to examine the effects of replacing chemical fertilizers with vinasse and filter cake during ethanol production (Moore et al., 2017). These scenarios were developed for the period of 2011- 2015, and the changes were quantified based on a substitution approach, through screening governmental document and literature (Moore et al., 2017).

There are several papers (23% of the total review case studies) which did not clarify the studied timeframe. The remaining papers studied the change in the product system for short or medium to long term. The short timeframe is every 30 minutes, hourly or monthly, and this was applied in five studies (Collinge et al., 2018; Elzein et al., 2019; Herbert et al., 2016; Roux et al., 2017; Roux and Peuportier, 2013) which were recently conducted on power/ heat generation systems. For medium to long term timeframe, there were 56 papers, accounting for 55% of reviewed case studies, ranging from three to 21 years of cycle crop or lifecycle of the product system (Fukushima and Chen, 2009; Glogic et al., 2019; Kimming et al., 2015, 2011; Styles et al., 2016) to 10, 20, 30, or 40 years. The studied timeframe ranged up to 200 years of forecasting scenarios, with product system of a 6 MW bio heat plant in UK (Brander, 2017).

3.2.3. *Applications of economic models*

59 out of 102 case studies did not apply any economic modelling. They conducted a C-LCA by developing different scenarios taken from governmental reports and plans, and identifying marginal/ affected technologies based on change in carbon flows or reviewing historical LCA studies, journal papers and published plans with results of economic model simulations.

The remaining 43 papers applied one or several economic models, in combination with LCA to model the indirect environmental changes. An example of coupling economic models and LCA is presented in Figure 11. Among papers that coupled economic models and LCA, the most frequently applied approaches include Partial Equilibrium

Model (PEM), General Equilibrium (GE), Input-Output (IO), Agent Based Modelling (ABM) and System Dynamic (SD) models. A third of papers used several models in combination, i.e. concurrently applying PEM + GE, or PEM + IO, or GE + IO. The application of dynamic model such as ABM and SD is less common than equilibrium and IO models.

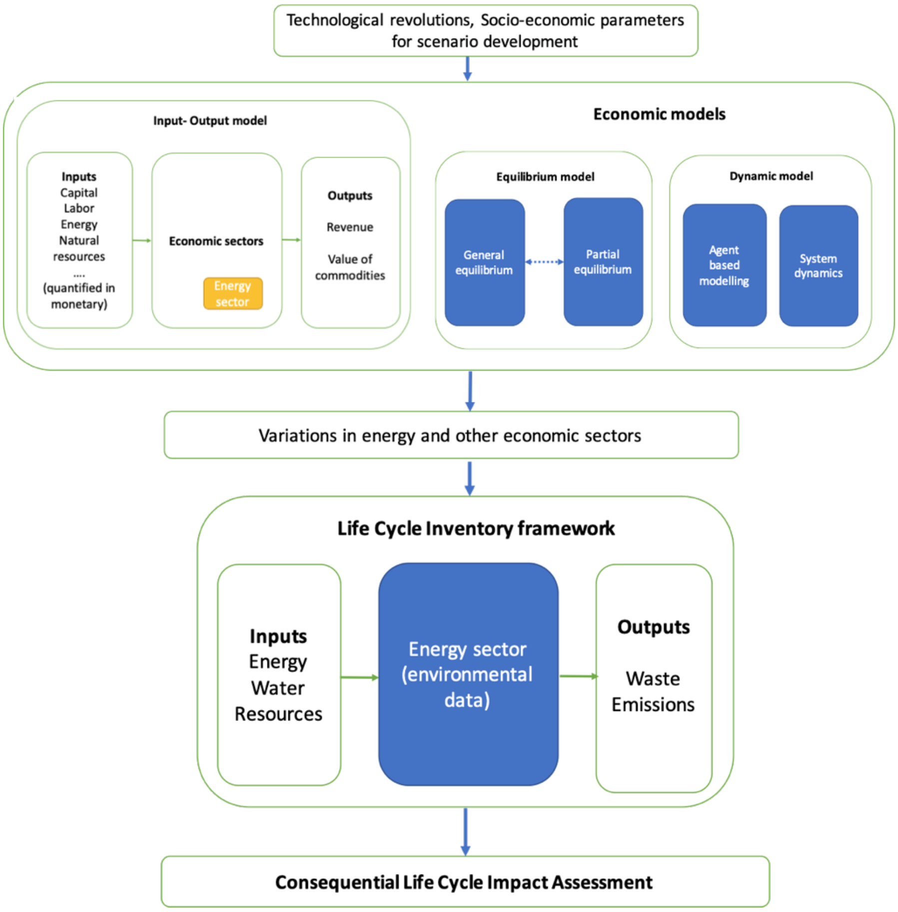


Figure 11 . Economic models and LCA for consequential LCA (adapted from (Igos et al., 2015)

3.3. Consequential life cycle environmental impacts of energy power system

3.3.1. Energy sector

In the energy sector, there is a difference between the direct and total environmental impacts, which is shown in many studies on LCA of energy systems such as fossil fuels, biofuel and bioelectricity. Prapaspongsa et al. conducted a C-LCA on Thailand biofuel and indicated that the inclusion of both direct and indirect environmental impacts highly affected the total environmental gains and losses of biofuel compared with the conventional diesel system (Prapaspongsa et al., 2017). Specifically, the impact of climate change of 14 million litres palm biodiesel with ALCA is 10,502 tCO_2e, while it is 4,599 tCO_2e with C-LCA (Prapaspongsa et al., 2017). Moreover, the impact of freshwater eutrophication is 5.88 t P e and -2.5 t P e, with ALCA and C-LCA respectively.

A large number of studies indicated that, due to off-site effects, the environmental life cycle impacts of bioenergy are larger at global scale when indirect impacts are included (Canals et al., 2006; Dandres et al., 2011; Oladosu, 2012; Pehme et al., 2017; Rege et al., 2015; Styles et al., 2016; Tonini et al., 2016, 2012; Yesufu et al., 2019). For example, the global warming potential of bioenergy, when indirect land use change effects are included, increased by three to eight times depending on types of plant based bioenergy (Styles et al., 2015). Similarly, the global warming impact of bioenergy in Denmark ranges from -82 and 270 tCO_2e per ha over 20 years with inclusion of indirect land use change. These figures are much higher than those of similar studies without consideration of indirect land use change, at -360 to 700 tCO_2e per ha over 20 years in Ireland, -500 tCO_2e per ha over 20 years in Italy, or -210 to -220 tCO_2e per ha over 20 years in UK (Tonini et al., 2012).

3.3.2. Power sector

In the power sector, C-LCA is successful in simulating the indirect environmental impacts. When the indirect impacts are included, the total environmental impacts that being assessed with C-LCA are either larger or smaller than those being assessed with ALCA. This was observed in several case studies that reported both direct and indirect environmental impacts results such as Pehnt et al., Dandres et al., Igos et al., Frischknecht and Stucki, Raugei et al., Vandepaer et al., Blanco et al. and McDowall et. al. (Blanco et al., 2020; Collinge et al., 2018; Dandres et al., 2011; Frischknecht and Stucki, 2010; Igos et al., 2015; McDowall et al., 2018; Pehnt et al., 2008; Raugei et al., 2018; Vandepaer et al., 2019a) (see Table 13).

Pehnt et al. studied the increase of off-shore wind power in Germany and its GHG emission reduction. The increased off-shore wind power substituted for thermal power from coal, lignite and gas, causing change in the power mix, operation of power system, expansion and reinforcement of the grid. The study indicated that in the low and high carbon certificate price scenarios, respectively, the specific carbon reductions per kWh offshore electricity in the year 2020 amount to 914 and 646 gCO_2e, thanks to the substitution of thermal power (Pehnt et al., 2008). The inclusion of the offshore wind power into the power system also affected the operation of thermal power plants and caused the loss in its operational efficiency, as a consequence, increased the GHG emissions of wind power, up to 70 and 18 gCO_2e per kWh of off-shore wind power. The emission from wind induced grid extension is 22 gCO_2e per kWh. When the emissions from all processes, including construction, operation and disposal of the wind energy park, wind-influenced grid expansion, carbon reductions due to thermal power substitution and GHG emissions from altered power plant operation were added up, the total net carbon reduction is 822 gCO_2e per kWh and at 606 gCO_2e per kWh (Pehnt et al., 2008).

Dandres et al. assessed the environmental impacts of EU electricity and heat generation in two EU energy policies, namely baseline and bioenergy, in consideration with and without global economic development. The quantified impacts included direct impacts of increased energy generation and indirect impacts due to change global economic activities served for increased energy generation in the EU. It was indicated that potential indirect impacts were higher than direct impacts, with impacts occurring inside the EU border only accounted for 5.5% of the total global potential impacts. Interestingly, indirect impacts of increased energy in bioenergy policy were considerably higher than those in baseline policy (Dandres et al., 2011). In other words, bioenergy policy which harnesses more renewable energy is regarded as being cleaner compared to the baseline policy, in fact causes more environmental impacts due to its indirect consequences on global economic activities.

Igos et al. assessed the impacts on human health, ecosystem and resources of two energy policies: BAU and GHG. The environmental impacts included direct impacts from energy related processes (energy production: gate to gate contribution of energy technology and energy import: cradle to gate contribution of the imported fuels and electricity processes to the final impact) as well as indirect impacts (contribution of changes in other economic sectors and imports). The contribution of indirect impacts was up to 50% in all three impact categories. The environmental impacts in GHG policy were 2-3% lower than those in BAU policy. This difference mainly and directly came from the energy sector. The contribution of other sectors to the difference of two policies environmental impacts was less than 0.1% (Igos et al., 2015).

Frischknecht and Stucki used attributional and consequential (decisional) life cycle inventories to quantify the environmental impacts of French and EU electricity supply (Frischknecht and Stucki, 2010). The attributional life cycle inventory was taken from Ecoinvent database and the consequential life cycle inventory was based on EurElectric, other energy publications and expert opinions. The authors identified that there was a difference between the obtained results. In the French electricity supply mix, the GHG emissions rose from 98 gCO_2e per kWh with ALCA to 225 gCO_2e per kWh with C-LCA. The volumes of high radioactive waste generated was 11 and 3.8 mm^3 per kWh, respectively (Frischknecht and Stucki, 2010). Similarly, in the EU attributional and decisional electricity supply mix caused GHG emissions of 554 and 473 gCO_2e per kWh and generated high radioactive waste of 3.5 and 3.4 mm^3 per kWh, respectively (Frischknecht and Stucki, 2010).

Raugei et al. conducted a C-LCA on the increased uptake of solar pv on UK grid. The increase of solar pv capacity impacted the generation mix as well as the grid development, and consequently global warming potential of solar pv (Raugei et al., 2018). The authors identified that there was a small difference in the GHG emissions from the increased solar pv deployment, which originated from background stages of solar pv and changes in the generation mix (Raugei et al., 2018). Consequently, any change in the solar pv deployment had no considerable additional emissions of the UK on-grid power (Raugei et al., 2018) (Raugei et al., 2018).

Vandepaer et al. quantified the environmental impacts of inclusion of battery into the Swiss power system by 2030. In the current policy scenario, the inclusion of battery caused the displaced electricity mix which was dominated by natural gas combined-cycle units (Vandepaer et al., 2019a). The inclusion of batteries generated environmental benefits in 12 of the 16 impact categories, including climate change, ozone depletion, particulate matter, ionizing radiation, photochemical ozone formation, acidification, terrestrial eutrophication, freshwater eutrophication, marine eutrophication, land use and water resource depletion. In low carbon scenario, marginal electricity generation being displaced due to the inclusion of batteries mostly came from geothermal and hydropower which already had reduced environmental impacts. Therefore, the environmental benefits due to inclusion of battery reduced compared to those of current policy scenario (Vandepaer et al., 2019a).

Blanco et al. conducted an ex-post LCA analysis of results from JRC - EU - TIMES and estimated the environmental impact indicators across 18 sectors in scenarios that achieved 80-95% GHG emission reductions by 2050 in EU28+ countries. The results showed that the indirect CO_2 emission was as large as the direct one for 80% reduction target. Moreover, for 95% reduction target, the indirect CO_2 emission was three times larger than the direct one (Blanco et al., 2020).

In the study of McDowall et al., the indirect emissions contributed to less than 10% of the total emissions of power sector in EU by 2050 (McDowall et al., 2018) , which was a small part, especially compared to the result of Blanco et al.'s study. It should be noted that while Blanco et al.'s study covered 18 economic sectors, the indirect emissions in McDowall et al.'s study includes that from energy equipment and construction (Blanco et al., 2020; McDowall et al., 2018). Moreover, in spite of the small contribution of indirect emission of power sector in McDowall et al.'s study, the inclusion of these emissions into the optimization model of the power system made the renewable power less attractive and consequently, induced changes in the structure of the power sector (McDowall et al., 2018).

Table 13 . Direct and indirect environmental impacts of some reviewed C-LCA papers

Studies	Product system	Environmental impacts/ benefits	Direct impacts only	Indirect impacts included	Variation
Pehnt et al. (Pehnt et al., 2008)	Wind power	GHG emission reductions (gCO_2e/kWh)	914 ~ 646	822 ~ 606	-10.1% ~ -6.2%
Dandres et al. (Dandres et al., 2011)	Electricity and heat	Environmental impacts	N/A		5.5%
Igos et al. (Igos et al., 2015)	Energy (including power)	Human health, ecosystem and resources	N/A		50.0%
Frischknecht and Stucki (Frischknecht and Stucki, 2010)	Power system (French)	GHG emissions (gCO_2e/kWh)	98	225	129.6%
		High radioactive waste (mm3/kWh)	11	3,8	-65.5%
	Power system (EU)	GHG emissions (gCO2e/kWh)	554	473	-14.6%
		High radioactive waste (mm3/kWh)	3.5	3.4	-2.9%
Raugei et al. (Raugei et al., 2018)	Solar pv	GHG emissions	N/A		±2%
Vandepaer et al. (Vandepaer et al., 2019a)	Lithium metal polymer battery	Climate change ($kgCO_2e/MWh$)*	7.89	-443	-5714%
	Li-ion battery		6.68	-439	-6671%
Blanco et al. (Blanco	Energy (including power)	GHG emissions (85% emission reduction target policy) (gCO_2e/kWh)	N/A		50%

et al., 2020)		GHG emissions (90% emission reduction target policy) (gCO_2e/kWh)	N/A	200%
McDowall et al. (McDowall et al., 2018)	Power sector	GHG emissions	N/A	10%

Notes:

N/A = Not available. No number on direct and indirect impacts was provided in the studies (Blanco et al., 2020; Dandres et al., 2011; Igos et al., 2015; McDowall et al., 2018; Raugei et al., 2018). Instead, these authors presented the results on variations between “direct impact only” and “indirect impact inclusion”.

* These numbers were estimated by the authors based on Figure 3 of Vandepaer et al. (Vandepaer et al., 2019a).

The mismatch between the total environmental impacts of power sector with and without indirect impacts was indicated by the cost of power generation. Algunaibet et al. quantified the life cycle indirect cost of electricity generation in the US and pointed out that other indirect environmental impacts of the power sector need to be considered apart from direct GHG emissions. In the study, the costs of electricity were minimized with constraints on demand, generation potential and capacity factor, while achieving a particular target on emission. These costs included levelized cost of electricity (direct cost) and costs to endpoint life cycle indicators including human health, ecosystem diversity and resource availability (indirect cost, externalities) (Algunaibet et al., 2019). It was found that by meeting the emission reduction of Paris Agreement, the indirect costs of electricity generation could be reduced up to 63% (Algunaibet et al., 2019). In contrast, the withdrawal from Paris Agreement would cause to a cost up to 1103 ± 206 billion USD 2013 in BAU scenario by 2030 (Algunaibet et al., 2019). When both direct and indirect costs are optimized, the total cost for the energy system is 373 ± 164 billion USD 2013 in 2030 (Algunaibet et al., 2019).

Elzein et al. assessed the GHG emissions and the operating cost of electricity generation of Normandy grid with the inclusion of energy storage system. The inclusion of energy storage system altered the generation of thermal and nuclear power plant, consequently, reduced the GHG emissions by 53%. At the same time, the operating cost reduced by 28% compared to the base case of historic power generation without energy storage system (Elzein et al., 2019).

It is indicated that there is a difference in the obtained results of reviewed C-LCA papers on quantifying the indirect and total environmental impacts. The variation ranges widely from inconsiderable difference (less than 5%) to 200%, depending on the investigated product system. In most of the case, the GHG emission and other environmental impacts are larger with the application of C-LCA, compared to ALCA. The variations in GHG emission quantifying results also impact the cost for GHG emission reduction in power system.

3.4. Economic models for C-LCA

Among reviewed papers, the numbers of studies using the PEM are much larger than those using the two latter models, with 11 studies compared to two studies applying GE and five studies applying IO, and two studies applying DM. More interestingly, it is common that the studies apply several types of economic models, for example, PEM in combination with GE, and PE in combination with IO. The applications of PEM, GE, and IO have the advantage of available data and (energy) economic models. Meanwhile, The DM is limited in terms of the availability of data and modelling tools, but works well with socio-economic data (L. Luu et al., 2020). Table 14 presents the reviewed C-LCA case studies and their applicable models.

Table 14. Applicable tools in reviewed studies

Study	PEM	GE	IO	DM	LR	Expert based
Dandres et al. (Dandres et al., 2011)		Y			Y	
Eriksson et al. (Eriksson et al., 2007)	Y					
Pizarro-Alonso et al. (Pizarro-Alonso et al., 2018)	Y					
Pehnt et al. (Pehnt et al., 2008)	Y					
Blanco et al. (Blanco et al., 2020)	Y					
Mathiesen et al. (Mathiesen et al., 2009)			Y		Y	
Lund et al. (Lund et al., 2010)			Y			
Igos et al. (Igos et al., 2015)	Y	Y				
Gibon et al. (Gibon et al., 2017)			Y		Y	Y
McDowall et al. (McDowall et al., 2018)	Y		Y			
Raugei et al. (Raugei et al., 2018)	Y					
Algunaibet et al. (Algunaibet et al., 2019)	Y					
Vandepaer et al. (Vandepaer et al., 2019a)	Y				Y	Y
Elzein et al. (Elzein et al., 2019)	Y					

Choi et al. (Choi et al., 2012)	Y					
Jones and Gilbert (Jones and Gilbert, 2018)			Y			
Florent and Enrico (Florent and Enrico, 2015)				Y		
Onat et al. (Onat et al., 2016)				Y		
Hammond and O'Grady (Hammond and O’Grady, 2017)	Not clear				Y	Y

Notes:

Y = Yes

Hammond and O'Grady presented three pathways to a low-carbon power sector of the UK by 2050, through coal phase-out, and technological innovations in CCS, and combined heat and power. These pathways were developed through Stakeholders workshop; Quantitative research; and Interdisciplinary workshop. The authors mentioned applying economic models and interdisciplinary assessment in the ‘quantitative research’ step; however, it is not clear which models have been used (Hammond and O’Grady, 2017).

3.4.1. Partial Equilibrium Model

Conceptual model

The PEM explains the behaviour of supply and demand of the product system as one part of the economy. The product systems, which are considered with PEM, can be any product of the economic activities and does not limit to the energy sector. This economic model focuses on the primary relations of supply, demand and price of the product system, and considers the product system as being partial closed to other economic sectors, i.e. the impacts of other economic sectors on the product system can be linked by changing parameters and variable exogenously (Vazquez-Rowe et al., 2013).

This type of model analyses the immediate or primary effects of economic disturbance, or the possible effects of a policy on one or several markets, in which any change in the price will induce a change in the supply and demand of the product system. There are three endogenous variables in the PEM: supply, demand and price, which are determined by the solution of the model (see equations 1, 2 and 3 for a simple PEM). There are also several coefficients or parameters to reflect the reactions of demand and supply to the price. Depending on the specific PEM modelling tools, there are several exogenous parameters such as Gross Domestic Product (GDP), inflation, population growth, price of input material, investment capital for technology, etc., which impact either supply or demand. The equilibrium price solution of the model can be obtained by setting demand being equal to supply.

The mathematical equations for PE are presented as followings:

$$Q_d = Q_s \tag{1}$$

$$Q_d = a - bP \tag{2}$$

$$Q_s = cP - d \tag{3}$$

In which:

Qd is the demanded quantity of the commodity;

Qs is the supplied quantity of the commodity;

P is the price of the commodity.

a, b, c, d are fixed or exogenous coefficients/ parameters, which can be altered depending on the specific PE modelling tool, for example, GDP, population growth, price of input material, and investment capital for technology.

Operational model

The PEM has been coupled with LCA to estimate indirect environmental impacts originating from the market force (Ekvall, 2002). For example, Bouman et al. cited in (Earles and Halog, 2011) examined the effectiveness of several tax instruments in reducing the amount of mined, landfilled, and emitted lead from batteries. Ekvall and Andrae cited in (Earles and Halog, 2011) explored the impacts of the lead solder ban in the electronics industry. Earles et al. analysed energy demand scenarios in case more wood is used for ethanol production (Earles et al., 2013). Vazquez Rowe et al. assessed environmental changes in the agricultural sector in Luxembourg linked to an expected increase in maize cultivation for energy generation (Vazquez-Rowe et al., 2013).

Due to the fact that the PE model considers the product system without connection to the rest of the economy, the coupling of PE and LCA is frequently applied to an industry or an economic sector (Katelhon et al., 2016). Several authors clarified that the PEM and LCA coupling is suitable to study one or two closely related sectors with 5 to 20 products (Beaussier et al., 2019; Pehnt et al., 2008). This is true for all reviewed case studies which applied PE and LCA, with a focus on one sector of energy production (Algunaibet et al., 2019; Blanco et al., 2020; Choi et al., 2012; Collinge et al., 2018; Dandres et al., 2017; Elzein et al., 2019; Jones and Gilbert, 2018; Pehnt et al., 2008; Raugei et al., 2018; Roux et al., 2017; Vandepaer et al., 2019a, 2019b), or two sectors of energy production and waste management (Eriksson et al., 2007; Pizarro-Alonso et al., 2018) or energy production and agriculture/ forest/ crop growing (Albers et al., 2019; Earles et al., 2013; Escobar et al., 2017; Menten et al., 2015; Rege et al., 2015; Rozakis et al., 2013; Tonini et al., 2017; Vadenbo et al., 2018, 2017; Vazquez-Rowe et al., 2014, 2013).

The coupling of PEM and LCA is mostly applied in macro geographic areas. Most of the reviewed PEM and LCA case studies (19 out of 24) were conducted at the national level. There are four case studies using PEM and LCA at the regional scale, e.g. expanding the geographical boundary to several countries by including import and export. Katelhon et al. and Beaussier et al., who agreed with this point, identified that the geographical boundary of PEM ranges from macro to meso scale (Beaussier et al., 2019; Katelhon et al., 2016). Interestingly, one case study used PE and LCA at the global level to identify the long-term marginal electricity supply mixes of 40 countries between 2015 and 2030 (Vandepaer et al., 2019b).

The coupling of PEM and LCA can run in various time horizons, either very short or medium, long term. For the very short term, PEM-LCA was applied to identify the impacts of marginal energy production and consumption hourly, monthly or even every 30 minutes (Collinge et al., 2018; Elzein et al., 2019; Roux et al., 2017). The medium and long terms are common among the reviewed case studies, with up to 20 papers conducting a C-LCA over the time frame of 15 to 20 years, and one paper with the time frame of 40 years.

The high percentage of coupling PE and LCA in the energy sector among reviewed case studies indicated that it seems to be the most common tool. This may originate from the availability of energy system modelling tools, which are mostly based on PE principle, such as NELSON, E2M2, Euroelectric, Energy 2020, ETM-UCL, Balmore, TIMES, MIRET, MARKAL, Network Impact Assessment Model, Emissions Reduction Cooperation Model, Energy Techno-Economic Model, JRC-EU-TIMES. The coupling of PE and LCA, therefore, takes the advantage of available data of energy system modelling tools.

PEM and LCA models can be coupled following these steps:

- run the PE model to obtain the marginal data, and
- run the LCA model to quantify the environmental impacts related to the changes in the product system.

As the two models of PEM and LCA are run independently, it is time-consuming and costly to match PEM results and LCA. There may be an incompatibility between the outputs of PEM and life cycle inventory databases, for example, marginal products obtained by PEM are not directly matched with Ecoinvent – the most common life cycle inventory database (Earles et al., 2013). At the same time, the independence of the two models also requires each PE model for every LCA (Eriksson et al., 2007). In spite of these limitations, it is possible to match the outputs of PE and the life cycle inventory database. The outputs of PEM include marginal technologies and energy production which are used as the inputs of energy consumption in the LCA model.

The coupling of PEM and LCA offers the efficient modelling of consequential effects based on economic indicators. It can model indirect environmental impacts due to simple changes in supply, demand and price (Beaussier et al., 2019). Eriksson et al. compared five combined heat and power technologies based on waste incineration and combustion of biomass or natural gas in Sweden. At a different fuel price, there is a change in the marginal electricity production and consumption (coal-based or renewables-based), and consequently in the technologies' environmental profiles (Eriksson et al., 2007). Pehnt et al. analysed the potential CO_2 reduction of offshore wind power. At different certificate prices, the operation and expansion of the electricity mix of renewable and conventional power plants turned to be altered, which consequently changed the net CO_2 reduction of offshore wind power (Pehnt et al., 2008). Escobar et al. combined PE and LCA to determine the feedstock combination for domestic biodiesel production in Spain and quantified its associated impacts. The PEM was used to predict the optimal feedstock mix based on farmers' and biodiesel plant owners' welfare. Depending on the types and origins of the feedstock mix, the GHG savings of biodiesel were altered (Escobar et al., 2017).

The coupling of PEM and LCA offers a detailed assessment of a specific product. Therefore, the C-LCA of one product cannot be applied to other similar products. Eriksson et al. and Pizarro-Alonso et al. applied PE and LCA in waste-based energy generation in Nordic countries and Denmark, respectively (Eriksson et al., 2007; Pizarro-Alonso et al., 2018). These two studies applied the same methodology to the same product system in a similar context. Therefore, it is expected there should be similarities among these studies. However, the studies convey two different results. In Eriksson et al.'s study, the results showed that waste incineration is better than landfill, but worse than recycling. On the other hand, Pizarro-Alonso et al.'s study showed climate benefits of waste trade at present as well as in long term. The only similarity in the two studies' results is that the environmental benefits of waste-based energy generation are sensitive to waste management approaches (landfill or recycle) and energy policy (energy importing/ exporting countries, marginal electricity mix), which were determined by simulations of PEM for energy system development and waste management system.

3.4.2. General Equilibrium Model

Conceptual model

The GE model explains the behaviour of supply and demand of the product system in the economy as a whole. It considers the supply, demand and price of the product system in relation to those of other economic sectors. GE expands the modelling to indirect effects of economic disturbances of different sectors on the market on the studied system (Beaussier et al., 2019; Katelhon et al., 2016; Vazquez-Rowe et al., 2013).

Similar to PEM, there are three types of endogenous variables in the GE: supplies, demands and prices, which are determined by the solution of the model (see equations 4, 5, and 6). There are also several coefficients or parameters to reflect the reactions of demands and supplies of the commodities to the prices. The solutions of the model are at equilibrium, the prices would satisfy the requirement that the demands equal the supplies of all markets for different commodities simultaneously.

The mathematical equations for GE are presented as followings:

$$Q_{i,d} = Q_{i,s} \tag{4}$$

$$Q_{i,d} = a_{1,\dots,n} - b_{1,\dots,n} P_{1,\dots,n} \tag{5}$$

$$Q_{i,s} = c_{1,\dots,n} P_{1,\dots,n} - d_{1,\dots,n} \tag{6}$$

In which:

$Q_{i,d}$ are the quantities demanded of the commodities;

$Q_{i,s}$ are the quantities supplied of the commodities;

$P_{1,\dots,i}$ are the prices of the commodities;

i are the commodities, ranging from 1 to n;

a, b, c, d are fixed constants parameters of the economy and commodities, which can be altered depending on the specific GE modelling tool.

Operational model

The GE model (and its variant Global Trade Analysis Project (GTAP) was coupled with LCA to assess the indirect environmental impacts in relation to market or policy changes in the whole economy. For example, Dandres et al. quantified potential global environmental impacts on human health, global warming, natural resource and ecosystem due to changes in the EU's bioenergy policy and bioenergy generation, respectively (Dandres et al., 2012, 2011). Oladosu studied the impacts of increased bioenergy use in the US on global GHG emissions (Oladosu, 2012). Dunn et al. evaluated global GHG emissions due to land use change for bioethanol in the US (Dunn et al., 2013). Other authors even combined several economic models of GE, PEM and IO with LCA, such as Igos et al. evaluated the EU's GHG emissions due to the energy policy of Luxemburg (Igos et al., 2015); or Some et al. studied change in bioenergy policy of US and EU, and its implication on global GHG emissions (Some et al., 2018).

The GE model considers the product system in relation to the whole economy, as a result, the coupling of GE and LCA covers a large number of sectors and includes several regions. All reviewed case studies cover several economic sectors and regions, specifically 20 economic sectors in 13 regions (Dandres et al., 2012, 2011), 33 economic sectors in 18 regions (Oladosu, 2012), 16 economic sectors in Luxembourg (Igos et al., 2015). Apart from one case study being conducted at the national level to quantify regional impacts (Igos et al., 2015), the remaining six case studies applied GE and LCA to assess the global environmental impacts due to changes at the national level (Dandres et al., 2012, 2011; Dunn et al., 2013; Marvuglia et al., 2013; Oladosu, 2012; Some et al., 2018).

The coupling of GE and LCA shows the highest effectiveness in medium to long-term studies. All reviewed case studies were conducted for at least 15 years and up to a 30-year horizon, for example, 15 years from 2006 to 2020 (Some et al., 2018), 25 years from 2005 to 2030 (Igos et al., 2015), policy by 2030 with GTAP running from 2005 to 2010 (Dandres et al., 2012), 20 years from 2005 to 2025, with GTAP running in 5-year steps (Dandres et al., 2011), policy by 2030 and GE running from 2001 to 2010 (Oladosu, 2012), and by 2040 (Dunn et al., 2013). There is no study applying GE and LCA for modelling short-term changes, for example, several years of crop cycle or hourly/daily power/heat generation, which can be observed in studies combining PEM and LCA.

The coupling of GE and LCA provides comprehensive outputs thanks to dealing with indirect environmental effects due to changes in supply, demand, and price of product systems on different economic sectors. GE-LCA allows to study significant changes affecting large systems with a global modelling of the economy (Dandres et al., 2011).

It extends the modelling to off-site effects of other economic sectors on the studied product system (Beaussier et al., 2019). Dandres et al. compared the results of PEM and GE-based C-LCA on bioenergy policy and identified that while the indirect environmental impacts of bioenergy policy are insignificant when being quantified with PEM-based C-LCA, they constitute the main part of the total environmental impacts in the GE based C-LCA approach (Dandres et al., 2012). Due to the improved modelling of interactions among economic sectors, the GE and LCA coupling is deemed to perform better in quantifying indirect impacts.

GE and LCA are coupled by running a GE model (mostly Global Trade Analysis Project or its variants) to predict economic disturbances caused by changes in policy or market. These disturbances will cause changes in demand and production in all economic sectors. The obtained data is then mapped with inventory databases to quantify life cycle environmental impacts (Dandres et al., 2011). Due to the incompatibility between the GE results and life cycle inventory, it would require effort to combine the two databases (Dandres et al., 2011). Also, due to this incompatibility, some processes or commodities are not available in either GE or life cycle inventory, consequently, they have been excluded or other similar processes are used (Dandres et al., 2011). This causes uncertainty in the obtained results.

In order to increase the detail of the studied sector, the input data required for GE models is directly taken from the PEM simulation or indirectly taken from literature which are results of PEM simulations to develop policy/market scenarios of the studied product system (Dandres et al., 2012, 2011; Igos et al., 2015; Marvuglia et al., 2013). Therefore, it would double the time for data collection and scenario development to conduct a GE-based C-LCA study, compared to PEM-based C-LCAs. Moreover, the application of several approaches would again hinder uncertainty during GE and LCA coupling.

In contrast with the comprehensiveness results offered by GE based C-LCA, one of its limitations is the low detail at the product level. The affected products and the affected processes of the product life cycle cannot be clearly identified (Beaussier et al., 2019; Ekvall, 2002; Katelhon et al., 2016). In the GE model, each main product corresponds to one economic sector. If there is any change in the manufacturing process of the product, or any technological revolution occurring during the product's life cycle, GE models the change by reducing or increasing the commodity inputs for manufacturing that product. Therefore, in order to identify the origin of the environmental impacts of the product system, several sensitivity analyses need to be conducted. For example, in order to identify whether the environmental impacts mostly come from imported or domestic commodity inputs, we need to conduct a lot of sensitivity analyses, by decreasing or increasing the value of these inputs.

At the same time, there are tens to hundreds of technologies for manufacturing a product in practice. Therefore, the technological efficiency is modelled in GE as being average in each economic sector. On one hand, it is impossible to model the substitution effects among alternative technologies (Katelhon et al., 2016), for example, introducing a new technology to manufacture an existing product. On the other hand, it is impossible to trace the rebound effect of technological efficiency (Dandres et al., 2011), as technology efficiency reduces the price and increases the consumption of the product, which is in contrast with the modelling principle of GE of reducing commodity inputs in case of technological revolution.

3.4.3. Input – Output Model

Conceptual model

The IO model describes economic flows, including production, consumption, employment and import/export, and their interrelations among different economic sectors and final users (Beaussier et al., 2019). It allows the calculation of the impact for entire sectors or economy rather than focusing on specific processes (Blanco et al., 2020). It shows how parts of an economic system are affected by a change in one part of that system (the interdependency among industries) in the economy (Beaussier et al., 2019).

The IO model explains the relationship between the total outputs of all economic sectors and the final demand for goods and service (see equation 7). The technological coefficients determine the output requirements for each economic sector to satisfy the demand for goods and service. Any changes in the final demand or the technological coefficients will cause a change in the needed outputs.

IO model is based on the following equation (Cellura et al., 2011):

$$X = (I - A)^{-1}Y \quad (7)$$

In which:

X is the vector of the total outputs needed to satisfy the final demand;

Y is the vector of the final demand of goods and services;

I is the identity matrix;

A is the matrix of technological coefficients.

Operational model

The coupling of IO (and its variant Environmental Extended Input Output (EEIO) and LCA has been used to simulate the indirect impacts of changes in products' inputs and outputs of several economic sectors. Mathiesen et al. and Lund et al. coupled LCA and EnergyPLAN to identify marginal energy technologies, applied in the Danish energy system (Lund et al., 2010; Mathiesen et al., 2009). Cellura et al. assessed the energy and environmental impacts related to the consumptions of Italian households in the period 1999–2006 and identified the economic sectors involving the highest impacts (Cellura et al., 2011). Katelhon et al. used an IO model (Technology Choice Model) in combination with the suboptimal decision and factor constraints to determine the marginal GHG emissions of different biomass energy technology mixes (Katelhon et al., 2016). Sherwood et al. characterized the food, energy and water intensities of the US economic sectors (Sherwood et al., 2017). Gibon et al. assessed the human health and ecological impacts of the global low-carbon electricity over its life cycle (Gibon et al., 2017).

The coupling of IO and LCA provides a comprehensive presentation of the economy, covering 50 industries in all economic sectors in a large geographical coverage (Beaussier et al., 2019), or up to 428 sectors (Sherwood et al., 2017). It was also applied at global scale (Gibon et al., 2017). However, in Katelhon et al.'s study, IO-LCA was used to capture a part of the economy, with a narrow spatial boundary, which assessed the thermal generation and climate change impact in a hypothetical rice plant in a province of Pakistan (Katelhon et al., 2016).

Similar to PE-based C-LCA, the coupling of IO and LCA was either applied for a short-term horizon (Lund et al., 2010; Mathiesen et al., 2009), with hourly change in the energy system, or for long-term effects of technological or policy changes (Gibon et al., 2017; McDowall et al., 2018; Some et al., 2018). The IO-LCA does not consider time series, it normally accounts for the impacts at a static time (Cellura et al., 2011; Katelhon et al., 2016; Sherwood et al., 2017).

As IO is based on data from all economic sectors of a country/region(s), the coupling of IO and LCA may take advantage of public data such as World Input-Output Database (Timmer et al., 2015) to develop an IO table (Cellura et al., 2011). The IO model also shares a similar computational framework with LCA (Sherwood et al., 2017), so it requires less effort to collect the data as well as run the model. However, there is a disagreement in the literature in the requirement of data for the IO and LCA coupling. According to Katelhon et al., IO-LCA requires more data than PE/GE-LCA (Katelhon et al., 2016).

The coupling of IO and LCA shows its effectiveness also in modelling both direct and indirect environmental impacts of a product system due to changes in other product systems. The modelled consequential effects include both simple, direct and off-site impacts of the economy thanks to the exhaustive background modelling (Beaussier et al., 2019; Cellura et al., 2011). The case study of Some et al. also showed that the coupling of GE, IO and LCA enables a broader consideration of the environmental effects of biofuel policies than conventional LCA (Some et al., 2018).

One limitation of IO-LCA is that it is based on a fixed price. In other words, the changes in demand or supply of the product are independent from its price. In order to model the interaction of price, Lund et al. developed two scenarios of open and closed electricity markets (Lund et al., 2010). In the open market, the model considers the connection of the studied energy system with the regional grid, and the electricity price is affected by the fluctuation in the regional grid market. In the closed market, electricity prices are determined by the production costs of the marginal production unit at a given hour. These two scenarios of price, together with technical constraints and optimized operational cost, were put into IO-based C-LCA to calculate the hourly marginal electricity and heat production unit to meet the demand (Lund et al., 2010).

Similar to GE-based LCA, the IO and LCA coupling is complained for its lack of detail at the product level. It assumes that there is only one product per industry, consequently, the process is not fully described (Sherwood et al., 2017). Therefore, the technology revolution in the IO-LCA is modelled to be unchanged. Only in McDowall et al.'s study, apart from the scenario of no technology change, the authors considered the change in the process in response to decarbonization policies (McDowall et al., 2018). As the authors combined PE, IO and LCA, they can take advantage of the PE model simulations of the decarbonization rate of the industry sectors producing energy technologies.

Interestingly, the study of Katelhon et al. proved that the coupling of IO and LCA can provide details at the technology level (Katelhon et al., 2016). They applied an IO model to determine the marginal GHG emissions of different biomass energy technology mixes. The IO model allowed one product is produced by several technologies, without considering the cost factor. The technology mixes are determined by factor constraints such as demand and natural resources, and the inclusion of a sub-optimal decision on the optimized cost pathway. The six scenarios of technological mixes utilized the engineering-level data therefore providing high level of technological/sectorial detail (Katelhon et al., 2016).

3.4.4. Dynamic Model

In terms of conceptual models, the coupling of dynamic modelling and LCA has been used to assess the impacts of dynamic interactions of a product system over its life cycle. The common dynamic models include ABM and SD. ABM simulates the effects of one agent on the system, while SD considers different agents' interactions in the system as a whole.

Specifically, in the energy sector, the ABM and LCA have been coupled to assess the life cycle environmental impacts of dynamic product systems. Specifically, Davis et al. computed the contribution of energy technologies to global warming in case a policy on the carbon tax is implied while considering the demand, supply and profit of the technologies (Davis et al., 2009). Miller et al. proposed a framework of ABM and LCA to understand the development of renewable energy technology for 20 years using Bayesian probabilities (Miller et al., 2012). Florent and Benetto assessed the environmental impacts of the electric vehicles under different mobility policies in Luxembourg between 2013 and 2020 (Florent and Enrico, 2015).

SD and LCA have been coupled to understand the impacts of the product under the systematic and dynamic interactions over time. Onat et al. assessed the life cycle sustainability of conventional, electric, hybrid and plug-in hybrid vehicles in the US from 2015 to 2050, in which seven sustainability impact categories are dynamically quantified (Onat et al., 2016).

The review indicates that the coupling of dynamic models and LCA is applied to one sector. This coincides with Beaussier et al.'s study, which clarified that ABM-LCA was frequently used for one (or several) product(s) of one sector (Beaussier et al., 2019), with one product (Davis et al., 2009; Marvuglia et al., 2017; Miller et al., 2012; Zhao et al., 2016) and four products (Florent and Enrico, 2015; Onat et al., 2016).

The coupling of dynamic models and LCA shows its effectiveness in modelling changes in the medium to long term. The changes in the product system are modelled for 8 to 40 years (Florent and Enrico, 2015; Marvuglia et al., 2017; Miller et al., 2012; Onat et al., 2016). Interestingly, the coupling of dynamic models and LCA offers the simulation for time serial, for example, one year step of product/ technology evolution (Marvuglia et al., 2017; Miller et al., 2012).

The combination of dynamic models and LCA performs well in modelling the technological change at a very micro level, but can also model the sector interactions at a very macro level. At the technological level, some authors applied ABM and LCA to evaluate the environmental impacts of an emerging technology. Miller et al. modelled the technology producing bioenergy from switch grass in the US, in which the adoption of technology is analysed under behaviour agents of individual resistance to change, profitability and familiarity on land adoption for biomass-based energy (Miller et al., 2012). In Florent and Benetto's study, the environmental impacts of four different types of electric cars are modelled with the decisional agents based on types of car, segment, consumption weight, travelling distance, and selling of car during the use phase under four policy scenarios (Florent and Enrico, 2015).

At the macro level, Onat et al. applied the SD-LCA to model the life cycle impacts of four different types of US vehicles in relation to three pillars of sustainability: economy, environment and society (Onat et al., 2016). The modelling, therefore, provides a comprehensive view of the sustainability of the US transport system (Onat et al., 2016).

The coupling of dynamic models and LCA works with socio-economic data. On one hand, it would be problematic to collect the specific behaviour and socio-economic data, which sometimes is unavailable (Florent and Enrico, 2015; Miller et al., 2012). Moreover, it causes a great deal of uncertainty due to the availability of data, and dependence on scenario and hypothesis (Florent and Enrico, 2015; Miller et al., 2012;

Onat et al., 2016). This limitation, consequently, makes it a predictive approach of forecasting how the change will occur more than for accounting purposes.

On the other hand, it performs well in modelling detailed systems with complex social and economic consequential effects, which is great in assessing sustainability over a product life cycle. In fact, the coupling of dynamic models and LCA is the only combination that can model the social impacts such as employment, public welfare, human health (Onat et al., 2016) and social behaviour such as farmers/producers' (Davis et al., 2009, Miller et al., 2012, Marvuglia et al., 2017) and consumers' decision (Florent and Enrico, 2015; Onat et al., 2016). As a result, it is suitable to the problems that are not totally driven by economic terms, but also social-behaviour driven.

CHAPTER 4. PROPOSED FRAMEWORK & DATA

Following the conceptual description of consequential life cycle assessment, this chapter will describe the operational model in detail. Based on an analysis of the strengths and limitations of available modelling tools, a hybrid framework of input output analysis and process-based LCA for conducting a C-LCA in the power sector will be proposed. The framework will be followed by a description of collected input data served for the calculation.

Similar to the previous chapter, this chapter will answer the same research question: What are the methods and approaches for quantifying and evaluating life cycle environmental impacts as consequences of changes? However, instead of focusing on the conceptual model in the previous chapter, this chapter includes a specific operational framework for conducting a C-LCA on the Italian power system.

4.1. Hybrid framework

4.1.1. Comparison of modelling tools

The PEM explains the behaviour of supply and demand of the product system as one part of the economy, which makes it a suitable tool to estimate indirect environmental impacts originating from the market force when being coupled with C-LCA. The coupling of PEM and LCA is frequently applied to an industry or an economic sector to model changes at the macro level, at the national or even global scales. The coupling of PEM and LCA can perform well in various time horizons, from the very short time frame to long-term period. Although it is simple to conduct PEM-based C-LCA, it cannot provide the technology or process details. The availability of PEM for the energy sector, and its relevant input data for the PEM running make it the most frequently used in coupling with LCA for quantifying both direct and indirect environmental impacts of the energy sector. Although there are complaints on the incompatibility between PE and LCA, it is possible to match the two approaches.

The GE model explains the behaviour of supply and demand of the product system in the economy as a whole, which makes the coupling of GE and LCA perform well in modelling indirect environmental impacts in relation to market and policy changes in the whole economy. The coupling of GE and LCA is suitable for modelling several economic sectors in a large number of regions, and it shows the highest effectiveness for modelling medium to long-term change. Therefore, it provides a comprehensive view of the product system in relation to the economy. Compared to PE, GE requires more time for collecting data and matching the obtained results to LCA models. Besides, its limitation lies in the incapability of modelling details at the product level.

The IO model describes the economic flows of different sectors in the society, therefore, the coupling of IO and LCA can be applied to model the indirect impacts of changes in products' inputs and outputs of several economic sectors. The coupling of IO and LCA can cover all economic sectors in a large geographical boundary. It can be applied for short-term to long-term horizons. Its strength lies in the effectiveness in modelling indirect impacts of a product system due to changes in other systems, with the availability public IO database and a similar framework with LCA. It limits in modelling principle of independence from price and lacks detail at the product level. However, some exceptional examples from the review indicate the application of IO-based C-LCA for modelling the causal relationship of price and product system, as well as providing the product details.

The dynamic model simulates the effects of one agent on the system (ABM) or considers different agents' interactions in the system as a whole (SD). The coupling of ABM and LCA is used to model the environmental impacts of a dynamic product system, for example, innovative technology, while the SD and LCA coupling is applied to understand the impacts of the products under complex systematic and dynamic interactions over time. The dynamic models and LCA coupling normally covers one economic sector, and a medium to long-term horizon. The coupling of dynamic models and LCA performs well in modelling technological change at a very micro level, and sector interactions at a macro level. Although it is quite complex to conduct a C-LCA based on dynamic models, the coupling shows the most effectiveness in modelling socio-economic indicators and offering diversified outputs of both quantitative and qualitative indicators of sustainability.

With the application of different modelling tools for C-LCA, it is expected that there will be a difference in the obtained results. For example, Dandres et al. assessed the bioenergy policy in the EU with PEM and GE and identified that with the application of PEM-based LCA, the global warming impacts are smaller compared to that obtained with GE-based LCA. With the application of GE and the inclusion of economic evolution, the potential impacts from China as an emerging market, caused a huge increase in the total global warming impact. For example, the potential life cycle impact of EU bioenergy policy in/from China is around $5*10^9$ $kgCO_2e$ with PEM-based

LCA, while this number is 2.5*10^{12} kgCO_2e with GE-based LCA (Dandres et al., 2011). This also happened to other markets such as South Asia, North America, Middle East and North Africa, etc. and other environmental impact categories such as human health, ecosystems and natural resources (Dandres et al., 2011).

Regardless of the used model, it is important to highlight that LCA studies have generally an intrinsic uncertainty related to various factors (i.e. difficulty in the survey of data, lack of detailed information sources, data quality, etc.) (Ardente et al., 2004). Thus, transparency of the studies and the use of sensitivity analysis are paramount for improving the reliability of the results (Ardente et al., 2003).

A summary of the different models for C-LCA is presented in Table 15.

Table 15. Features of the models for C-LCA

	PEM+LCA	**GE+LCA**	**IO+LCA**	**ABM+LCA**	**SD+LCA**
Application	- Apply for changes originating from the market force, disregard the whole economy - One industry or economic sector - Various time horizon	- Apply for changes originating from the market force, with regard to the whole economy - All economic sectors - Medium to long term	- Apply for changes due to economic interactions - All economic sectors - Various time horizon	- Apply to changes of one agent in a socio-economic context - One economic sector - Medium to long term	- Apply to changes in the whole system in a socio-economic context - One economic sector - Medium to long term
Input data	Price, demand of the studied product system, consumption of environmental inflows, and emission factors	Price, demand of all commodities, consumption of environmental inflows, and emission factors	Inputs, outputs of goods and service, consumption of environmental inflows, and emission factors	Cost, consumption pattern of the studied product system, environmental inflows, and emission factors.	Cost, consumption pattern of the studied product system, environmental inflows, and emission factors.
Obtained results	- Environmental and economic indicators (quantitative) E.g. Change in GHG emission (tCO_2e) and animal feed supply and demand (one ton of animal feed) over time due to increased bioenergy demand or power production Change in natural resource depletion (kg of used metal) and generation of different types of power (at an equilibrium power price) due to an increase in solar pv capacity and generation			- Environmental and socio-economic indicators (quantitative and qualitative) E.g. Changing pattern of land for energy crops over time due to change in bioenergy demand; changing area of land for energy crops (ha) due to change in farmer behaviour	

	Change in climate change impact (tCO_2e) and power production and structure of power system by 2030 (at a carbon price) due to policy on renewable portfolio standard			Dynamics of annual human health impacts for a 20-year period (DALY) due to the application of an energy policy Reduction in indirect cost (million USD) of electricity generation due to implementation of the Paris Agreement	
Strengths	- Availability of data and energy development model - Provide product detail	- Availability of data and global trade model	- Availability of public database - Share a similar framework with LCA	- Good at modelling technological changes at a micro level - Ability to work with socio-economic data	- Good at modelling technological changes at a macro level - Ability to work with socio-economic data
Limitations	- Incompatibility between PEM and LCA, but not too difficult to match two models	- Incompatibility between GE and LCA, and effort to match two models - Lack of product detail	- Price independence - Lack of product detail	- Difficult to collect data and complex to run the model	- Difficult to collect data and complex to run the model

4.1.2. Hybrid method of Input Output analysis for C-LCA

The coupling of economic models and life cycle assessment quantifies both direct and indirect environmental impacts of a product system to the extent of change in the technological development and socio-economic context. During the period of 2006-2020, the commonly used economic models includes PE, GE, input-output, agent-based modelling and system dynamics, in which the coupling of PE and LCA is the most frequent combination. There is a trend in combining several economic models such as PE and GE, partial equilibrium and input-output, and GE and input-output with LCA to get the highest effectiveness of each economic modelling tool.

The coupling of PE or GE and LCA estimates environmental impacts from the changes due to the market mechanism, with some strengths in the availability of modelling tools and relevant input data. PE or GE and LCA models are inharmonious in their databases and modelling approaches. It is not too difficult to match PE and LCA, while takes some effort to match GE and LCA. The coupling of input-output and LCA works well in modelling environmental impacts induced by economic changes thanks to the availability of public input-output databases and similar frameworks with LCA. However, the input-output and LCA coupling simulates the change with independence from price and lacks product details. The dynamic model and LCA combination simulate the social and environmental impacts, but running a dynamic model is complex and takes a lot of effort for collecting input data for the models. The choice of using one or more economic models combined with LCA may be determined by the goal of the study, the nature of the changes due to market mechanisms, economic or social origins, and the availability of data.

In this thesis, the hybrid method of input-output and process-based LCA has been selected to assess the consequential life cycle environmental impacts of the Italian power system. First, the technological and socio-economic parameters are collected for constructing the power and socio-economic development scenarios. These scenarios will be integrated into the input-output tables. At the same time, the process-based data will be included in input-output tables to provide the power system’s details. The combination model of input-output analysis and process-based LCA will be applied to obtain the results on consequential life cycle impacts of the Italian power systems in the context of climate change policy.

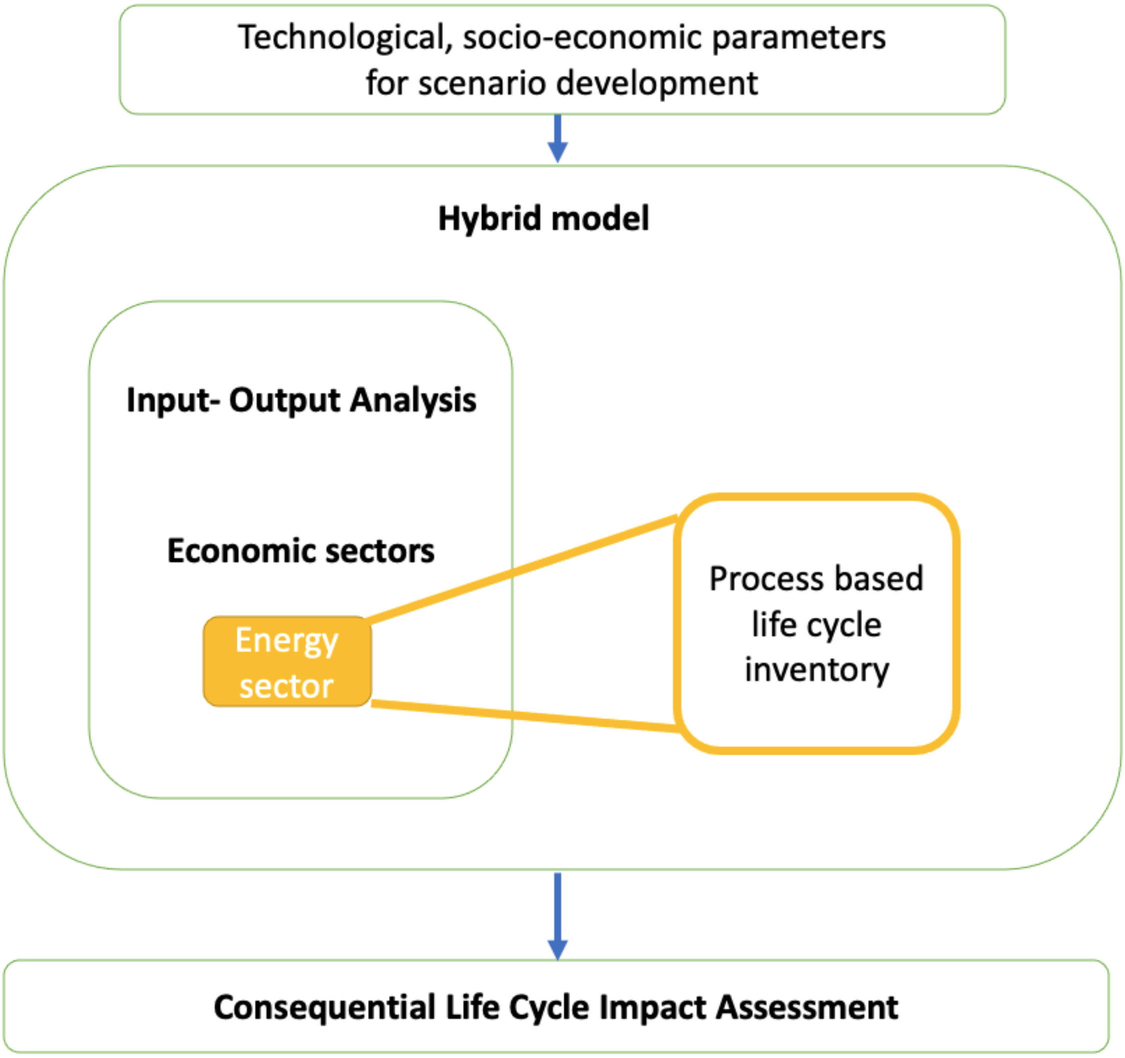


Figure 12. Framework of the hybrid method

The framework of the hybrid method is presented in Figure 12.

(1) First, two types of data, including input output data and data for the integration are collected. IO data such as the Italian and multiregional input output (MRIO) tables and NAMEA air tables are collected from Istat and EXIOBASE. data for the integration is collected from (Snam and Terna, 2021) for power development scenarios, and from the ecoinvent database for direct air emissions of power generation technologies. Detail of collected data will be presented in the next section.

(2) From IO data, the MRIO model with two regions of Italy and Rest of the World (RoW) and 36 economic sectors will be constructed.

(3) In combination with the power development scenarios, the Italian electricity sector is disaggregated into seven power generation technologies, for both intermediate flow matrices and final demand vectors in Italian IOT. Similarly, in the environmental burden matrices, the air emissions of electricity sector are

disaggregated into emissions of seven power generation technologies. At this time, the model composes of 42 sectors (36 economic sectors - 1 electricity sector + 7 power technologies). The mathematical equations for disaggregating different matrices and vectors will be presented in the next section.

(4) The model is calculated with historical data of 2010 and 2017 (reference scenario) and replicated for the future scenarios of 2025, 2030 and 2040. The simulation is conducted with Python.

4.1.3. Mathematical model for IO-based C-LCA

The consequential life cycle environmental impacts of further inclusion of renewable energy into the energy system will be calculated following these equations:

$$I_{LC} = \gamma(f) \qquad (8)$$

In which

I_{LC} is the total life cycle impacts of all products

γ is the environmental coefficient

f is the vector of products including *f1, f2, …, fn* products, $f = \begin{Bmatrix} f1 \\ f2 \\ \dots \\ fn \end{Bmatrix}$

Leontief equation to calculate the total gross output of the economy needed to meet the final demand, presented as followings:

$$X(f) = (I - A)^{-1} \times Y(f) \qquad (9)$$

In which

X(f) is the total gross output of the economy needed to meet the final demand

I is the identity matrix

A is the technological coefficient matrix

Y(f) is the final demand of products

Adapting the Leontief equation for quantifying the environmental impacts of industries and final consumptions to calculate the life cycle environmental impacts, we have:

$$I_{LC} = S \times X(f) = S \times (I - A)^{-1} \times Y(f) \quad (10)$$

In which

S is the pollution coefficient matrix

Providing that the renewable energy will be included into the energy system, at an amount δ, the life cycle impacts will change into *I'*

$$I'_{LC} = \gamma(f + \delta) \quad (11)$$

Similarly, applying the Leontief equation to quantify the life cycle impacts of all products *f* with the inclusion of renewable energy δ, we have:

$$I'_{LC} = S' \times X(f + \delta) = S' \times (I - A')^{-1} \times Y(f + \delta) \quad (12)$$

In which

I'_{LC} is the 'after-change' life cycle impacts (life cycle impacts after the inclusion of renewable energy)

S' is the 'after change' pollution coefficient matrix

A' is the 'after change' technological coefficient matrix

$Y(f + \delta)$ is the 'after change' final demand of products (final demand of products, with the inclusion of demand on renewable energy)

Now, we will have the consequential life cycle impacts of renewable energy I_{CLCA}, calculated with the following equation:

$$I_{CLCA} = I'_{LC} - I_{LC} = S' \times (I - A')^{-1} \times Y(f + \delta) - S \times (I - A)^{-1} \times Y(f) \quad (13)$$

Similar concepts of C-LCA, which induces the formation of equation (13) can be found in (Schaubroeck et al., 2021). The Leontief's equation can be found in (Leontief, 1970)

In this study, the consequential life cycle impacts of renewable energy will be modelled by creating different scenarios of developing the energy systems to 2040. The year 2017 will be used as the baseline or the 'before change' scenario and scenarios of

2025, 2030 and 2040 are the 'after change' ones. Because there are several 'after change' scenarios', the scenarios will be indicated by the time (t) for the simplification. For example, S_{2030} denotes the 'after change' pollution coefficient matrix in 2030; Y_{2025} denotes the 'after change' final demand in 2025.

The consequential life cycle impact will be quantified from both production-based and consumption-based perspectives in a multiregional context, presented as followings:

$$F^i_{pba} = F^i_s e + F^i_y \qquad (14)$$

$$F^i_{cba} = My^i + F^i_y \qquad (15)$$

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

F^i_s is the direct emission of production activities of region I; e is an appropriate summation vector

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

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

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

From the production-based perspective, the emissions include direct emissions from production activities plus emissions from final consumption. Meanwhile, from the consumption-based perspective, the emissions composes of emissions from all activities to meet the final demand. In other words, it includes emissions from domestic production plus import, and excluding exports. In the multiregional context, the global emissions will be the same in case of being quantified from different perspective. However, at national scale, the differences in emissions embodied in import and export will cause the difference in emissions from production-based and consumption-based perspectives.

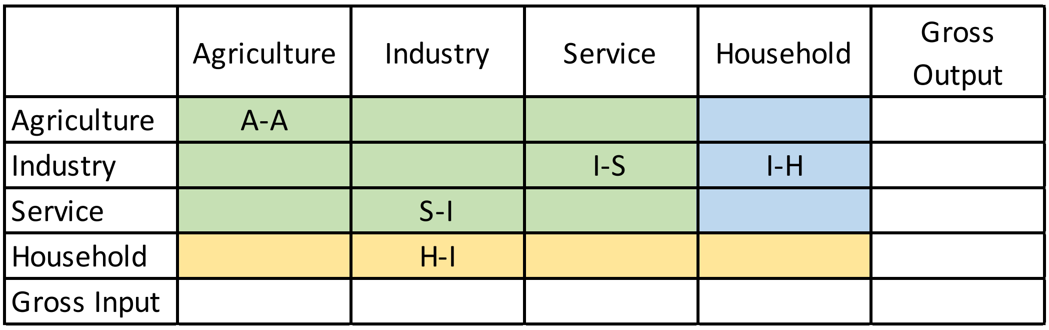
4.2. Data

4.2.1. Inter-industrial Coefficient Matrices

The inter-industrial coefficient matrices A present the relationship among different industries (or sectors) of an economy, in which products (or outputs) of one industry are used as inputs of other industries, or in other ways, indicate the inter-industrial relations of the amount (or value) of intermediate products to produce other products. The A matrix in the baseline scenario (before change) is developed based on the input output tables (IOTs). While the data for A matrix in future scenarios (after change) is the combination of IOT with the integration of power development scenarios. The following section will describe the data collection for A matrices in different years of

2017, 20125, 2030 and 2040, specifically the introduction on IOTs and procedures for integrating future energy development scenarios in IOTs (A matrices of future years).

The first concept of Input Output Analysis (IOA) was introduced and developed by Wassily W. Leontief since the 1920s'. After about 60 years of studying on this topic, his collection of journal papers has been published in the "Input-Output Economics" book, containing the concepts and various applications of IOA. Basically, IOA is an economic method for understanding the socio-economic interactions within the production industries and between the production activities and final consumption, in relations to material and resource consumptions, labor use and price[11](Leontief, 1951). These socio-economic interactions are structured into input output tables (IOTs). A simple IOT is presented in Figure 13 below.



	Agriculture	Industry	Service	Household	Gross Output
Agriculture	A-A				
Industry			I-S	I-H	
Service		S-I			
Household		H-I			
Gross Input					

Figure 13. A simple Input Output Table

The rows of the IOT present outputs of sectors being distributed among sectors, and the columns indicate needed inputs from different sectors. In Figure 13, it is assumed that the economy includes four sectors, namely agriculture, industry, service and household, with four corresponding outputs including agricultural products, industrial products, service and labour (provided by the household sector, presented by the yellow cells in Figure 12). By columns, there are three production sectors[12] of agriculture, industry and service (presented in green cells) and one consumption sector of household (presented in blue cells). By rows, these four sectors provide outputs which will be used as inputs for themselves and other sectors. For example,

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[11] Leontief, 1951. Input Output Economics, Chapter 1, pp.5-14

[12] Though being called as "production sectors", these sectors play the roles of both producers and consumers. They produce intermediates for other production sectors and final products/ service for consumption sectors. At the same time, they use intermediates produced by other production sectors and labor from the household sector. This is also the case of consumption sectors. The terms production or consumption sector are used to present the different between supply (production sectors) vs demand (consumption sectors); and material input requirement (provided by production sectors) and labor requirement (provided by households).

the cell A-A is the amount of agricultural product of the agriculture sector used for this sector's own purpose. The cell I-S is the amount of industrial products of the industry sector supplied for the service sector. Vice versa, the cell S-I is the amount of service supplied by the service sector for the industry sector. The cell H-I presents the amount of labour of the household sector used in the industry sector. As outputs of one sector will be used as inputs for other sectors, the gross output (the last column in Figure 13) equals to the gross input (the last row in Figure 13).

One distinguishing feature of IOA is the capacity of presenting complex transactions among industries and between industry and final consumption. Firstly, we can see the industry purchase of intermediate inputs (and labour use) are connected to the other sectors' outputs, which are the interrelations among industries, presented in green cells (and the first three yellow cells) in Figure 12. At the same time, we can see that the industry purchase of inputs is determined by final consumption, which are the links between blue cells and green cells in the Figure. For example, the final consumption of industrial products (cell I-H) is connected to the uses of agricultural products, industrial products, service and labour in the industry sector.

The inter-industrial relationship indicates the technological structure, which includes the coefficients of each intermediate input Z to the gross output X of the corresponding industry, or the ratio of green cells dividing by the first three rows of the gross output column in Figure 12. This is called the inter-industrial coefficient matrix or A matrix[13].

The Italian IOT has a breakdown of the economy into 63 industrial sectors, corresponding to 63 products. The classification of sectors and products follows the classification of sectors/ products by activity (CPA), with reference to NACE A*64. The coding structure of CPA corresponds to that of NACE up to the fourth level[14] (Eurostat, 2008). The final consumption composes of the final consumption of households, of non-profit social institutions serving households (ISP) and of public administration related to distribution and redistribution of income. Besides, there are final payments including inventory changes, export and investment. The final consumption together with the final payment will make up the total expenditures. The sum of industry purchasing and total expenditure is gross output. Similarly, the sum of industry

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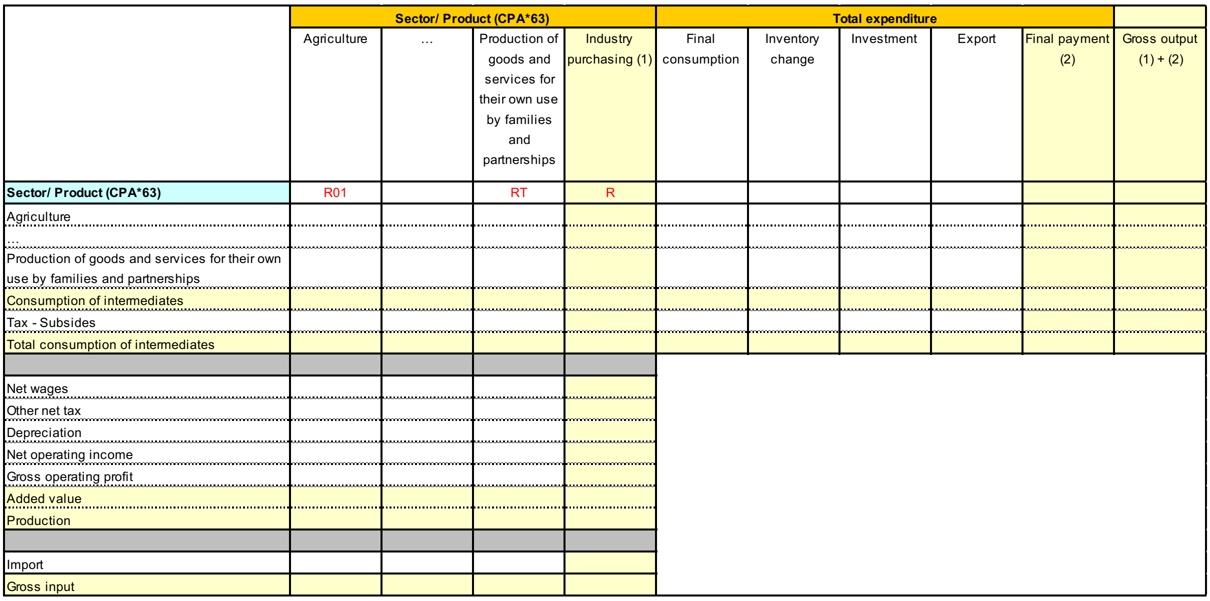
[13] The A matrix is different from the T matrix which is normally used in process-based LCA. Both matrices show the relation between the intermediate inputs and final product outputs. However, A matrix is based on economic or monetary value of industries, for example €, while T matrix is based on physical requirement of technologies.

[14] NACE Rev 2 guideline p.42

production and total accumulation is gross input. The structure of Italian IOT is presented in Figure 14 below.



	Sector/ Product (CPA*63)				Total expenditure					
	Agriculture	…	Production of goods and services for their own use by families and partnerships	Industry purchasing (1)	Final consumption	Inventory change	Investment	Export	Final payment (2)	Gross output (1) + (2)
Sector/ Product (CPA*63)	R01		RT	R						
Agriculture										
…										
Production of goods and services for their own use by families and partnerships										
Consumption of intermediates										
Tax - Subsides										
Total consumption of intermediates										
Net wages										
Other net tax										
Depreciation										
Net operating income										
Gross operating profit										
Added value										
Production										
Import										
Gross input										

Figure 14. Structure of Italian Input Output Table

The Italian IOTs are published every five years by ISTAT. The most updated IOT was published in 2017, therefore, in this study the IOT for 2017 was used. The corresponding A matrix with 63 product-by-product of the Italian IOT for 2017 (A_{2017}) is presented in Appendix A.

If we assume that any change in the product system will contribute to a small part of the economy, the ‘before change’ A and ‘after change’ A matrix would be similar. However, it is not the case for the energy/ electricity sector. In fact, the inclusion of renewable energy and energy efficiency measures into the energy system will induce changes in the A matrix. It would directly cause changes in electricity sector in matrix A, consequently changes relevant economic sectors providing inputs for the electricity sector direct and indirectly.

The changes in the electricity sector and relevant economic sectors are modelled by integrating the power development scenarios into the A matrix. With the integration of these scenarios, the ‘before change’ A matrix will become the ‘after change’ A. In these cases, the ‘before change’ A matrix is the baseline of 2017 (A_{2017}) and the ‘after change’ A matrices are matrices of future scenarios with the changes in energy-related sectors (A_{2025}, A_{2030} and A_{2040}) the ‘before change’ A matrix will be integrated with power development scenarios of corresponding future years to obtain ‘after change’ A matrix. For energy supply development scenarios, the data of Terna and Snam will be used. The power development scenarios has been described in detail in Chapter 2.

During the integration of energy supply development scenarios into the A matrix, the scenarios are adapted to the electricity sector and cause corresponding changes on other economic sectors. In Italian IO tables, the electricity, gas and steam sector is divided into three subsectors. (1) Electricity supply subsector includes electric power generation, transmission, distribution and trade. (2) Gas supply subsector includes the manufacture of gas and the distribution of natural and synthetic gas to consumers. (3) Steam and air conditioning supply includes production, collection and distribution of steam and hot water for heating, power and other purposes, production and distribution of cooled air, production and distribution of chilled water for cooling purpose and the production of ice for food and non-food purposes. The details of these subsectors will be discussed in Section 3 on "Aggregation and dis-aggregation of matrices".

As mentioned in Chapter 2 CHAPTER 2. ENERGY CLIMATE POLICY AND ITALIAN ENERGY SECTOR, the Italian electricity generation technologies in 2017 comprise of natural gas-based power, coal and other fossil fuels-based power, hydropower, wind power, solar power and other RE-based power. By 2025-2040, the generation mix will change towards a decrease in fossil fuels and an increase in RE. Table 16 below is the combination of Table 9 and Table 10 in Chapter 2, with the grouping of power generation technologies. It indicates the percentage of power generation technologies contributing to the grid mix between 2017 and 2040. These data of the National Trend Italy developed by Terna and Snam will be deployed for the energy supply development scenarios.

Table 16. National Trend Italy scenarios

Share of technologies (%)	**2017**	**2025**	**2030**	**2040**
Coal and other non-RE (oil)	12.9	2.4	1.5	0.8
Gas (natural gas and others)	44.4	41.6	27.9	25.9
Solar (with CSP)	5.4	11.9	20.6	21.9
Wind	7.5	9.1	11.8	17.8

Hydropower	11.1	14.9	14.4	13.8
Other RES (geothermal, biogas, solid and liquid biofuel)	7.1	7.0	6.8	6.5
Net import/ export	11.6	13.1	17.1	13.3
Total percentage (%)	**100**	**100**	**100**	**100**

The IOTs published by ISTAT divided the economy into 63 products/ sectors, and do not offer any details in electricity sectors. Meanwhile, the energy supply development scenarios of Terna and Snam present a detail development plan for the energy sector, by different energy technologies, including import and export. Therefore, the disaggregation of the energy sector in IOTs into detailed energy technologies is crucial in order to match the IOT and energy development scenarios.

For the disaggregation of the energy sector into detailed energy technologies, a row vector of electricity share v_{es} will be created, in which the columns of the vector are the shares of detailed energy technologies. The sum of the columns equals to one.

The disaggregation of the energy sector is presented in matrix A_{ele}, which is calculated with the following equation:

$$A_{t-ele} = v_{t-es}^{T} * A_{2017-ele} * v_{t-es} \quad (14)$$

In which:

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

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

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

v_{es}^{T} is the transpose vector of v_{es}

The consumption of inputs from different economic sectors for the production of the energy sector are presented in matrix $A'_{oth,ele}$ and calculated with the following equation:

$$A_{t-oth,ele} = m_{t-is} * v_{t-es} * A_{2017-oth,ele} \quad (15)$$

In which:

$A_{t-oth,\ ele}$ is the matrix for intermediate inputs from other economic sectors to the electricity sector in year t

$A_{2017-oth,\ ele}$ is the original matrix for intermediate inputs from other economic sectors to the electricity sector in 2017

m_{t-is} is the matrix of input supply from other economic sectors to the electricity sector in year t. The sum product of m_{is} and v_{es} equals to one.

The consumption of energy for different economic sectors are presented in matrix $A_{t-ele,oth}$. The flows of inputs and outputs between other economic sectors are presented in matrix A_{t-ind}. The matrices $A_{t-ele,oth}$ and A_{t-ind} are calculated with the following equation:

$$\begin{vmatrix} A_{t-ind} & \vdots & A_{t-ind} \\ A_{t-ele,oth} & A_{t-ele} & A_{t-ele,oth} \\ A_{t-ind} & \vdots & A_{t-ind} \end{vmatrix} = {Iv_{t-es}}^{T} * A_{2017} * Iv_{t-es} \quad (16)$$

In which

Iv_{t-es} is the identity matrix with cells representing inputs from the electricity sector to electricity technologies is replaced by vector electricity share v_{t-es}.

${Iv_{t-es}}^{T}$ is the transpose matrix of Iv_{t-es}

By substituting the results obtained by the equation 15 into the results obtained by the equation 16, we have the structure of disaggregated matrix A in year t is presented in following figure:

$$\begin{vmatrix} A_{t-ind} & A_{t-oth,ele} & A_{t-ind} \\ A_{t-ele,oth} & A_{t-ele} & A_{t-ele,oth} \\ A_{t-ind} & A_{t-oth,ele} & A_{t-ind} \end{vmatrix}$$

The disaggregated ‘before change' A matrix of the Italian IOT for 2017 and the disaggregated ‘after change’ A matrices for the years 2025, 2030 and 2040 are presented in Appendix B, C, D and E.

4.2.2. *Final Demand Vectors*

As mentioned in the previous section, IOTs present the link between the inputs used and outputs manufactured by the production sectors, and the final consumption. The final demand is vector Y (or vector of final consumption). In this study, data on the final demand, extracted from the Italian IOT for 2017 is utilized for vector Y_{2017}, which is presented in Appendix A.

For vector Y of future years (Y_{2025}, Y_{2030}, Y_{2040}), the total final consumption will include the additional final demand of the year 2025, 2030 and 2040. The total final demand of 2025, 2030 and 2040 is forecasted based on the total final consumption data of WB and OECD countries studies estimated for 2023, using linear regression.

The detail of final consumption for each economic sector are estimated based on the average shares of final consumption during the period 2015-2017. Besides, it is essential to disaggregate the final demand from electricity sector of the vector Y_{2017} as well as vectors Y_{2025}, Y_{2030}, Y_{2040} into the final demand of specific electricity supply technologies. This will be done by applying the following equation:

$$Y_t = {Iv_{t-es}}^T * Y_{t-agg} \qquad (17)$$

In which:

Y_t is the disaggregated final demand with detailed electricity technologies in year t

$Y_{t\text{-}agg}$ is the original final demand in year t

$Iv_{t\text{-}es}$ is the identity matrix with detailed electricity technologies

$Iv_{t\text{-}es}^T$ is the transpose matrix of $Iv_{t\text{-}es}$

The disaggregated vectors Y_{2017}, Y_{2025}, Y_{2030}, Y_{2040} are presented in Appendix F.

4.2.3. *Pollution Coefficient Matrix*

The pollution coefficient matrix S indicates the amount of pollutants F per total gross output X of the economy (which is similar for the S matrix of the ‘before change’ scenario as well as the ‘after change’ scenarios). The dataset for the ‘before change’ F matrix is taken from the National Accounting Matrix with Environmental Accounts Air Emissions (NAMEA-Air) of Italy. While the data for the 'after change' F matrix is the combination of NAMEA with the integration of power development scenarios. The following section will describe the data collection for F and S matrices, specifically the introduction on NAMEA and relevant environmental accounts, as well as procedures for updating NAMEA in future scenarios.

The matrix F is a combination of environmental account and economic statistics. In European countries, the Regulation (EU) 691/2011 provided a legal framework for data for environmental accounts. Under this framework, there are six compulsory modules. The six compulsory modules consist of Air Emissions Account (AEA); Economy Wide Material Flow Account (EW-MFA); Physical Energy Flow Account (PEFA); Environmental taxes; Environmental Goods and Services Sector accounts (EGSS); and Environmental Protection Expenditure Account (EPEA)[15] (Eurostat, 2021). Table 17 below presents features of different environmental account modules.

Table 17. Environmental accounts

AEA	recording the physical flows between the economic system and the air emissions. The economic system is divided into economic activities that generate air emissions, with differences between production (64 industries), consumption (households), trade, value added, and etc. 6 GHGs and 7 air pollutants are recorded in AEA (Eurostat, 2021).
EW-MFA	an economic wide balance sheet including all material flows between the economic system and the natural system. There are 50 material categories of biomass, metal ores, non- metallic minerals, and fossil energy materials. These flows are bi-directional, in which both material production and consumption are recorded (Costantino, n.d.; Eurostat, 2021).
PEFA	recording energy flows between the economic system and the environment. The recorded flows include energy flows from the environment to the economy (the use of natural inputs for energy products), within the economy (the use of energy products) and

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[15] Eurostat Statistical Explain

	from the economy to the environment (the generation of excess heat or energy residues (Eurostat, 2021).
Environmental taxes	Presenting environmental taxes of four categories: energy, transport, pollution and resource. In this account, the economic system is broken into 64 tax-paying sectors including industries and households (Eurostat, 2021).
EGSS	Presenting the supply flows of goods and service for environmental protection and resource management. It includes production and export of goods and service, value-added and employment, with a breakdown of 21 industries (Eurostat, 2021).
EPEA	Presenting the demand flows of goods and service for environmental protection. It includes expenditures for goods (including intermediate), import and export, investment, with a breakdown of four sectors (Eurostat, 2021).

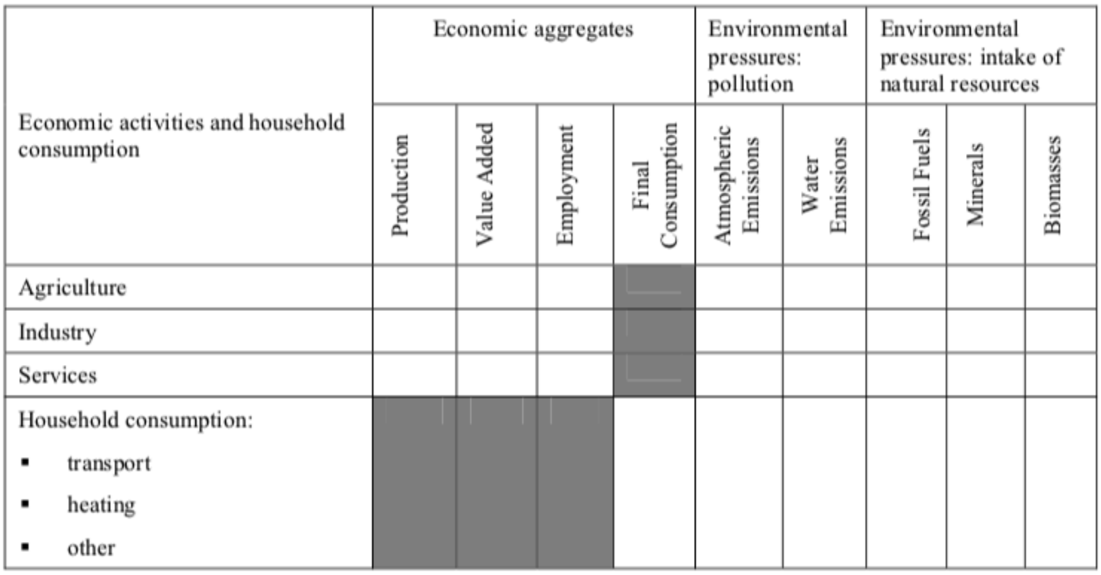
These modules are at different stages of maturity and their development has been set out in the multi-annual EU strategy for environmental accounts. The most updated strategy indicated the plan for development period of these accounts by 2023 (Eurostat, 2021). These environmental modules are the most standardized and globally widespread ones. Some environmental accounting modules developed in the EU such as AEA, EW-MFA and EPEA are also adopted outside Europe (Costantino, n.d.).

In addition to these six modules, other EU environmental accounts have been developed without EU legal basis, for example forest account, environmental subsidies and similar transfer account, ecosystem account and water account. Forest account covers natural assets such as wooded land and timbers; economic aspects of the forestry and logging industry; and environmental aspects such as wood balances, carbon capture of the forest. Environmental subsidies and similar transfer account records subsidies and other forms of government support measures that help to protect the environment. Ecosystem and water accounts provide information on natural resource extraction, e.g. ecosystem values and water consumption, respectively (Costantino, n.d.; Eurostat, 2021).

The AEA, water, energy, and other accounts on natural intakes are frequently grouped into one category of National Accounting Matrix with Environmental Account (NAMEA).

NAMEA was first developed since the 1990s by the European Union Statistical Office, with the aim of integrating the environmental data with the economic data recorded in the National Account framework (Eurostat, 2002) cited in (Gajos and Prandecki, 2016). It is a combination of national account data, for example, input output tables, and environmental accounts, for example, air pollutant accounts (Eurostat, 2009) cited in (Gajos and Prandecki, 2016). It presents the environmental and economic data of economic sectors and household consumption per monetary and physical units (Eurostat 2006) cited in (Gajos and Prandecki, 2016). Figure 15 below presents the structure of NAMEA (Costantino, n.d.).

Figure 15. Structure of NAMEA



Economic activities and household consumption	Economic aggregates				Environmental pressures: pollution		Environmental pressures: intake of natural resources		
	Production	Value Added	Employment	Final Consumption	Atmospheric Emissions	Water Emissions	Fossil Fuels	Minerals	Biomasses
Agriculture				▨					
Industry				▨					
Services				▨					
Household consumption: ▪ transport ▪ heating ▪ other	▨	▨	▨						

Among environmental aspects being considered in NAMEA such as air emissions, energy use, water use, wastewater, solid waste, etc, the most common and well-developed NAMEA tables are NAMEA-Air tables, presenting data for air pollution. NAMEA-Air was first constructed in 1999 in 11 pilot projects (Gajos and Prandecki, 2016). After several efforts of Eurostat in revising to harmonize tables of different countries, the 'standard' NAMEA tables were introduced in 2002 (Eurostat, 2004) cited in (Gajos and Prandecki, 2016). Nowadays, NAMEA-Air are available for all EU countries.

NAMEA tables on other compartments such as soil, water and resource extraction (from the nature) are less common. Some countries developed the national NAMEA tables for emissions to water, for example in Sweden, Denmark and Germany (Heijungs et al., 2006). Several countries have compiled NAMEA tables on energy, resource use, water use, wastewater and solid waste (Eurostat 2001) cited in (Gajos and Prandecki, 2016). In the Netherland, apart from air emissions such as GHGs, ozone layer depletion emissions, acidification and eutrophication, the Dutch NAMEA tables also cover wastewater, solid waste and exploration of crude oil and natural gas (Schanau et al. 2010) cited in (Gajos and Prandecki, 2016).

NAMEA-Air compilation guide list around 20 substances for inventory in three priority (Eurostat 2004) cited in (Gajos and Prandecki, 2016). Priority 1 includes GHGs (carbon dioxide, carbon dioxide from biomass, nitrous oxide, methane, hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride). Priority 2 includes some other substances such as nitrogen oxides, sulphur oxides, ammonia, non-methane volatile organic compound, carbon monoxide, particulate matter, chlorofluorocarbons, hydrochlorofluorocarbons, mercury, lead, and cadmium. Priority 3 includes some heavy metals: arsenic, zinc, chromium, selenium, copper, and nickel (Gajos and Prandecki, 2016).

Because there is no obligation for EU countries to construct NAMEA tables, NAMEA tables are constructed to the extent of the availability of data and resources (Gajos and Prandecki, 2016). For NAMEA-Air, data which is available on the Eurostat website cover emissions of nitrogen oxides, methane, nitrous oxide, carbon dioxide and sulphur oxides.

NAMEA-Air and AEA share the same concepts, definitions, classification, accounting rules and structures, which are also the same as those of systems of national accounts (SNA). The most important sharing features are the accounting principle and the residence principle, i.e. adopting a scope which is not based on territory but on the residency of producer units. This is the same scope used for gross domestic product (Eurostat, 2021, 2015)

The physical flow of NAMEA-Air include flows of gaseous and particulate material from the economic system (production, consumption and accumulation processes) to the natural environment, more specifically to the atmosphere.

For accounting principle, NAMEA-Air assign emissions to producing entities (or industries). These industries are composed of several local kind-of-activity units (or establishments) of the similar activities of producing goods or service. Apart from principal products and service, industries sometimes conduct one or several secondary activities with corresponding products/ service. Then, air emissions associated with both principal and secondary activities (or products/ service) need to be recorded under those industries. There are 64 industries in NAMEA-Air, using NACE A*64 classification (statistical classification of economic activities in the European Community), the same as supply and use tables, input output tables.

The residence principle defines the scope of the national economy and what is included in the account. NAMEA-Air records air emissions arising from activities of resident units constituting a given national economy, regardless of where the emissions occur physically. For example, if the industry is registered in Italy, and they provide freight transportation service between Italy and Spain. The emissions from the production of this industry's service are to be recorded in the Italian NAMEA as the industry' profit contribute to the Italian GDP. It should be noted that the national emission inventory under the EU Convention on Long Range Transboundary Air Pollutions (CLRTAP) and United Nations Framework Convention on Climate Change (UNFCCC); and the national energy statistics do not follow the same residence principle as applied in national accounts and NAMEA. National emission inventory and national energy statistics rather follow territory principle. i.e. the record emissions arising from the territory of a given country regardless who emits.

Emissions from transportation activities are assigned to the operators of transport vehicles or mobile sources of emissions. These operators are either industries or private households. Emissions from vehicles operated by tourists are attributed to the country of residence of the operators, according to the residence principle, regardless of the ownership of the vehicles. This is different from the principle of recording national emission inventory under CLRTAP and UNFCCC, and national energy statistics which do not consider the information about operators.

In NAMEA-Air, economic activities include consumption activities by private households. The emissions from private households are direct emissions arising from the consumption of products and service, to avoid double counting with production activities of industries. Households emits air pollutants through consumption activities in transportation, heating/ cooling and others.

The emissions covered in NAMEA-Air are anthropogenic emissions. Emissions from natural sources (volcanos, forest fires, etc.) are generally excluded. It should be noted that cultivated forest and domesticated animals are parts of the national economy, therefore emissions from these activities are recorded in NAMEA-Air. NAMEA-Air records the human made emissions in relation to the national economy, or the total economic activities of resident units, regardless of the geographical boundary where the emissions actually occur (residence principle). This is different from the territory principle of national emission inventory under CLRTAP or UNFCCC

Coverage of substance. NAMEA-Air include six GHGs, five air pollutants and two forms of particulate matters, namely CO_2 (CO_2 from biomass is separately reported), N_2O, CH_4, HFCs, PFCs, SF_6, NOX, CO, NMVOC, SOx, NH_3, PM_{10} and $PM_{2.5}$ (Eurostat, 2015).

The CO_2 emission is excluded CO_2 from biomass (wood, wood waste, charcoal, bio alcohol, black liquor, landfill gas, household waste being used as fuels) and the latter is treated as separate substance. CO_2 emissions are measured in 1000 metric tonnes. Other GHG emissions (N_2O, CH_4 and F-gas) are measured in metric tonnes CO_2-equivalents.

NOx includes nitric oxides and nitrogen dioxide, expressed as nitrogen dioxide (NO_2). It is measured in metric tonnes of NO_2-equivalents.

SOx includes sulphur dioxide, sulphur trioxide, sulphuric acid, hydrogen sulphide and other reduced sulphur compounds). It is expressed in metric tonnes of SO_2-equivalents.

NMVOCs means all organic compounds of an anthropogenic nature, other than methane, that are capable of producing photochemical oxidants by reaction with nitrogen oxides in the presence of sunlight.

Particulate matter (PM) is an air pollutant consisting of a mixture of particles suspended in the air. These particles differ in their physical properties (such as size and shape) and chemical composition

In Italy, several environmental accounts have been developed including EW-MFA, NAMEA, EPEA , Resource Use and Management Expenditure Account (RUMEA), etc. The EW-MFA of Italy is the same as regulations of the EU, presenting material flow indicators and balance sheets. NAMEA reports atmospheric emission, waste, emissions to water, fossil fuel, mineral, biomass and water extraction. EPEA and RUMEA of Italy is a combination of environmental taxes accounts, EGSS and EPEA of the EU framework. It records the production of goods and service for environmental protection; expenditures of enterprises, central and local government, households for environmental protection, and environmental taxes. Besides, Italy plans to develop the Integrated environmental and economic accounting for natural resources (NRIEEA) which composed of the accounts for forest, water, sub-soil assets, land and other natural resources (e.g. fish) (Costantino, n.d.). Table 18 below presents features and development stages of these Italian environmental accounts (compiled from (Costantino, n.d.))

Table 18. Italian environmental accounts

Environmental accounts	Features	Stage of development
EW-MFA	Same as EU framework	completed
NAMEA	reporting atmospheric emission (AEA in the EU framework), waste, emissions to water, fossil fuels, minerals, biomass and water extraction	Completed for air emissions, work-in-progress for other emissions and natural extraction, but feasible for the availability in the near future
EPEA and RUMEA	recording the production of goods and service for environmental protection (EGSS in the EU framework); expenditures of for environmental protection (EPEA in the EU framework, and environmental taxes (environmental taxes account in the EU framework.	Completed for EPEA, and initial investigation for RUMEA
Integrated environmental and economic accounting for natural resources (NRIEEA)	including accounts for forest, water, sub-soil assets, land and other natural resources	Initial investigation

Among these environmental accounts, NAMEA and NRIEEA are suitable sources for reference as they are relevant to the environmental inflows and outflows to air, water and land. NRIEEA has not completed or been available for publication. NAMEA has been completed for air emissions, and other accounts on water emissions or natural intake is under progress. Therefore, only NAMEA-Air (of Italy for the year 2017) is utilized in this study.

The Italian NAMEA-Air tables are published annually by ISTAT[16]. Italian NAMEA-Air tables include 10 atmospheric emissions, (including carbon dioxide, sulphur oxides, nitrogen oxides, nitrous oxides, ammonia, methane, carbon monoxide, non-methane volatile organic compounds and particulate matter $PM_{2.5}$ and PM_{10}) for 63 products/ production sectors (production activities) and three consumption sectors of transport, heating and others (consumption activities). Detail dataset of NAMEA-Air 2017 is presented in Appendix G.

For the 'after change' S matrix, we need to forecast the emission coefficients of the economy. The future emission coefficients depend on the 'after change' emission amount F and economic value, or total output 'after change' X. Data for the future total output is taken from economic forecast. The air emission amount of the economy will depend on the operation of all individual socio-economic sectors. While the emissions of GHGs largely depend on the types of fuels being used in the operation of economic activities, the emissions of other air pollutants (sulphur oxides, nitrogen oxides, ammonia, methane, NMVOCs and particulate matters) is closely connected with types of installation, types of equipment (Moorkens and Dauwe, 2019). Due to the complexity of applying changes in types of fuels, installation and equipment in different socio-economic sectors, the future emission amount is extrapolated based on the historical data of emissions during 2005 -2017 using linear regression.

First, the amount of air emissions F during 2005-2017 are normalized by the national GDP of corresponding years. The improvement factor of emission intensity per GDP is obtained from these calculations. Second, based on the calculated improvement factor of emission intensity, the amount of air emission of 2019 will be calculated and compared to that of NAMEA-Air 2019. Until the calculated air emission amount matches with the actual emission amount of NAMEA-Air 2019, then that improvement factor will be used for calculating the air emission amount for future years of 2025, 2030 and 2040.

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[16] http://dati.istat.it/Index.aspx?QueryId=10526&lang=en#

The air emission amount ‘after change’ F of each economic sector ij of the future years are calculated with the following equation:

$$F_{t-ij} = GDP_t * [e * (1+f)^{(t - t_0)}] \qquad (18)$$

In which:

e is the emission intensity per GDP of base year

f is the improvement factor

t is the forecasted year (2025, 2030 and 2040)

t_0 is the base year 2017

As mentioned above, NAMEA-Air shares the same framework and classification with IOT, with 64 industries/ sectors, and the emissions of the electricity sector is not further divided into specific electricity supply technologies. Therefore, the electricity sector of the original dataset of NAMEA-Air 2017 as well as that of the F matrix for future years of 2025, 2030 and 2040 is disaggregated seven electricity supply technologies. In order to disaggregate the electricity sector, the data set from Ecoinvent for air emissions of electricity supply technologies will be used. The below figure presents the disaggregated matrix F’ with the integration of Ecoinvent dataset into NAMEA-Air.

$$\begin{vmatrix} F_{t-oth,em} & F_{t-ele\,sec,em} & F_{t-oth,em} \\ \cdots & \cdots & \cdots \\ F_{t-oth,em} & F_{t-ele\,sec,em} & F_{t-oth,em} \end{vmatrix} \quad >> \quad \begin{vmatrix} F_{t-oth,em} & F_{t-ele\,tech,em} & F_{t-oth,em} \\ \cdots & \cdots & \cdots \\ F_{t-oth,em} & F_{t-ele\,tech,em} & F_{t-oth,em} \end{vmatrix}$$

Notes:

$F_{t\text{-}oth,em}$ are the emission amount of different economic sectors in year t. Each economic sector’s emissions are presented in one column.

$F_{t\text{-}ele\ sec,em}$ are the emission amount of the electricity sector, being presented in one column.

$F_{t\text{-}ele\ sec,em}$ are the emission amount of electricity generation technologies. There are seven technologies which are presented in seven columns.

It should be noted that the emissions of Ecoinvent data are more diverse than those of NAMEA. Therefore, the two database need to be matched. The matching rules follow the description on the coverage of substances of NAMEA in the previous texts. Each emission is presented in one row, and there are 10 rows representing CO_2, N_2O, CH_4, NOx, SOx, NH_3, NMVOC, CO, PM_{10} and $PM_{2.5}$.

The S_t matrix is calculated by dividing the disaggregated F_t matrix by the corresponding X_t vector in year t and presented in the following equation:

$$S_t = F_t / X_t \qquad (19)$$

In which:

S_t is the disaggregated emission coefficient matrix in year t

F_t is the disaggregated emission amount matrix in year t

X_t is the total output of the economy in year t

The disaggregated 'before change' S matrix of the base year 2017 and 'after change' S matrix of the future years of 2025, 2030 and 2040 are presented in appendix H, I, J and K.

As mentioned above, NAMEA-Air includes data for direct emissions of final consumption F_Y_{2017}, with three sectors of transport, heating and others. These emissions are emission from household consumption only, and includes 10 air emissions of CO_2, N_2O, CH_4, NOx, SOx, NH_3, NMVOC, CO, PM_{10} and $PM_{2.5}$. There is no available data on direct emissions of government, household serving institutions and investment; therefore, the emissions of these actors are set as 'zero'.

Similar to the calculation of 'after change' F, the air emission amount 'after change' F_Y of final household consumption of the future years are calculated with the improvement factor and corresponding GDP:

$$F\_Y_{t-ij} = GDP_t * [e * (1+f)^{(t-t_0)}] \qquad (20)$$

The data on direct emissions of final household consumption in of base year and future years are presented in appendix L.

4.2.4. Aggregation and dis-aggregation of matrices

The original Italian IO tables include 63 products/ sectors, which is the same for environmental account (NAMEA-Air for production activities). For the reference system, the sectors are aggregated into 36 production sectors (see Appendix K). For the consequential system, the sector of electricity and gas is disaggregated into seven electricity generation technologies, so there will be 42 production sectors at total (see Appendix K).

In Italian IO table, the electricity sector includes three subsectors of (1) electric power generation, transmission, distribution and trade of electricity, (2) manufacture of gas, distribution of gaseous fuels through mains, and (3) steam and air conditioning supply[17].

The production of electricity includes the operation of power generation plants, including thermal power plants, nuclear power plants, hydropower plants, gas turbine power plants and renewable power plants. This subsector excludes the production of electricity through incineration of waste (which is categorized in sector of waste management and disposal).

The transmission of electricity includes the operation of transmission systems that convey the electricity from the power generation plants to the distribution system.

The distribution of electricity includes the operation of distribution system such as lines, poles, meters and wiring that convey electric power received from the power generation plants or the transmission system to the final consumer.

The trade of electricity includes the sale of electricity to users, the activities of electric power brokers or agents that arrange the sale of electricity via power distribution systems operated by others and the operation of electricity and transmission capacity exchanges for electric power.

The manufacture of gas includes the production of gas for the purpose of gas supply by carbonation of coal from agricultural by-products or waste; and the manufacture of gaseous fuels with a specific calorific value, by purification, blending and other processes from gases of various types including natural gas. This subsector excludes the production of crude nature gas, operation of coke oven, manufacture of refined petroleum product and manufacture of industrial gas (which are categorized in sector of mining and quarrying)

The distribution of gaseous fuels through mains includes the distribution and supply of gaseous fuels of all kinds through a system of mains. This subsector excludes long

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[17] NACE Rev.2 guideline, p.204

distance transportation of gases by pipelines (which is categorized in sector of land transportation)

The trade of gas through mains includes sale of gas to users through mains, activities of gas brokers or agents that arrange the sale of gas over gas distribution systems operated by other and commodity and transport capacity exchanges for gaseous fuels. This subsector excludes wholesale of gaseous fuels, retail sale of bottled gas, and direct selling of fuel (which are categorized in subsector of whole sale and retail trade)

The steam and air conditioning supply includes the production, collection and distribution of steam and hot water for heating, power and other purposes, production and distribution of cooled air, production and distribution of chilled water for cooling purposes, production of ice, for food and non-food (e.g. cooling) purposes.

The electric power generation, transmission and distribution subsector was the largest part of electricity, gas and steam sector, contributing 82.42 % of the sectoral value added in 2017. The gas supply subsector was next largest in terms of value added with a 15.67 % share. Remaining 1.91 % of value-added was recorded in steam and air conditioning supply[18]. Therefore, it is assumed that the electricity generation technologies can be present for the technologies of the whole electricity, gas and steam sector.

Table 19 presents terminologies for matrices and vectors used in the equations in this Chapter.

Table 19 . Terminology for matrices and vectors

Z_t	Intermediate flows matrix in year t
A_t	Inter-industrial coefficients matrix in year t
I	Identity matrix
L_t	Leontief matrix in year t, equals to $(I-A)^{-1}$
Y_t	Final demand matrix in year t
X_t	Total gross output, equals to LY_t
F_t	Direct air emission amount matrix of production activities in year t
F_Y_t	Direct air emission amount matrix of final consumption in year t
S_t	Air emission coefficient matrix of production activities in year t

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[18] Eurostat data from https://ec.europa.eu/eurostat/databrowser/view/SBS_NA_IND_R2__custom_1438474/settings_1/table?lang=en

S_Y_t	Air emission coefficient matrix of final consumption in year t
t	Year (2017 is baseline for the reference system, 2025, 2030 and 2040 are future scenarios for the consequential systems)

CHAPTER 5. APPLIED FRAMEWORK INTO THE ITALIAN CONTEXT

This chapter presents the obtained results of applying the hybrid framework of IOA and process based LCA for consequential life cycle assessment on the Italian power system. The results are presented on two main points: (1) consequential life cycle assessment (C-LCA) impacts of Italian power sector, and (2) interactions among energy climate policy, power system and the economy. Besides, the methodological and operational framework will be discussed. Suggestions for future research are also provided in this Chapter.

5.1. Consequential life cycle environmental impacts of Italian power system

The production-based accounting (PBA) analyses the emissions according to where they actually generated. Firstly, it includes the emissions from all production activities. Secondly, it takes into account direct emissions from final consumption of households, government and investment. Here, the production-perspective considers households as producing units, in which they produce their private services namely heating and lighting their dwellings, driving their own cars and using electrical equipment. Some of these activities do not generate any PBA emissions such as lighting and using electrical equipment. The production perspective does not take into account the air emissions embodied in imported goods and services for intermediate production and for final use.

Meanwhile, the consumption-based accounting (CBA) takes into account the emissions from industries in order to create products for final use, including air emissions embodied in imports, and excluding air emissions embodied in exports. Air emissions embodied in export from one country will be accounted for consumers elsewhere.

In this case, the PBA indicates the direct air emissions from electricity production and consumption activities, while the CBA indicates direct and indirect air emission from final electricity consumption including imported and excluding exported electricity. Both PBA and CBA can be considered as 'life cycle' emissions/impacts, in which PBA implies the 'gate to consumer' emissions/ impacts and CBA covers the 'cradle to grave' system boundary. The air emissions and impacts are calculated for the power sector and per a functional unit of one marginal MWh of electricity.

5.1.2. PBA of marginal Italian electricity

During the period of 2017 -2040, the direct marginal air emissions of Italian electricity production and consumption are negative, indicating its contribution to the emission reduction of the nation. These reductions occur in all air emission categories, with different scales. Most of the emission reduction originates from coal and natural gas power, due to the reduction in the amount of electricity generated by these two technologies between 2017 and 2040. For the cases of NH_3 and NMVOC, most of NH_3 and NMVOC emission reductions come from other renewable electricity (electricity by biomass).

There is a difference in the pattern of change in the air emissions between three periods of 2017- 2025, 2017-2030 and 2017-2040 (as presented in Figure 16). The emissions reductions of NH3 and NMVOC are relatively large during the period of 2017-2025 and 2017-2030. However, these emissions reductions are much smaller during the period of 2017-2040. In fact, the electricity by other RES increases over three periods of 2017-2025, 2017-20130, and 2017-2040; in which the amount of electricity by other RES increase from 5.8 TWh in 2017 to 23 TWh by 2025 and 2030, and at peak by 2040, at 26 TWh. Considering the fact that most of NH3 and NMVOC emissions reduction come from other renewable electricity, this suggests the non-linear change in emissions pattern of electricity technologies and electricity sector as a whole.

For other air emissions, the emission reductions are quite similar among different periods of 2017-2025, 2017-2030 and 2017-2040. Specifically, the CO_2 emission reduction is 64.85 $MtCO_2$ by 2025, which reach the peak by 2030 at 75.34 $MtCO_2$, and followed by a slight reduction by 2040, at 71.56 $MtCO_2$. Most of the CO_2 emissions reduction originates from coal and natural gas power, due to the reduction in electricity generation amount of these two technologies between 2017 and 2040. The reductions of CO_2 as well as other air emission are presented in Figure 16.

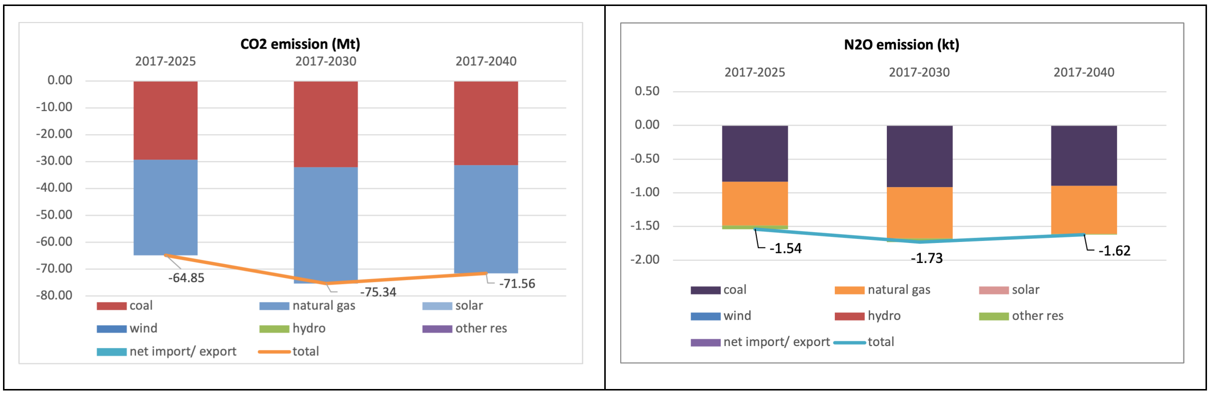


Figure 16. Production based emission reductions of electricity sector

The emissions of marginal electricity production and consumption per MWh do not follow the decreasing trend in the period of 2017- 2040. Between 2017 and 2025, there is a considerable reduction in all air emission categories per MWh, which is due to the comprehensive change in the power generation structure of increasing renewable energy such as solar and wind for power generation and the phasing out of coal-based electricity.

By 2030, air emissions slightly increase per MWh of marginal electricity production and consumption. However, the increase in air emissions per MWh does not mean that the emissions of the electricity sector as a whole increase (refer to the previous section). In fact, both the marginal air emission of the electricity sector and the marginal electricity generation decrease between 2017 and 2030, which makes air emissions per MWh become positive.

By 2040, the air emission reductions of one MWh of electricity are very small. However, this small reduction does not indicate that the air emission of one MWh of electricity by 2040 is similar to that of 2017. Although the air emissions reduce between 2017 and 2040, the increase in electricity generation and consumption of 2040 as compared to 2017 makes the air emissions reduction benefits become insignificant.

It should be noted that the air emissions changes are negative between 2017 and 2025, and between 2017 and 2040. Meanwhile, the air emissions change is positive between 2017 and 2030. This originates from the changes in marginal electricity generation, for which the marginal electricity generation increases between 2017 and 2025, and between 2017 and 2040; while it decreases between 2017 and 2030. This pattern of change suggests a non-linear decrease of marginal air emissions, in which the air emissions decrease, being independent from the increase or decrease of electricity generation.

Figure 17 below presents the air emissions of 1MWh of marginal Italian electricity in the period 2017-2040 from the production perspective.

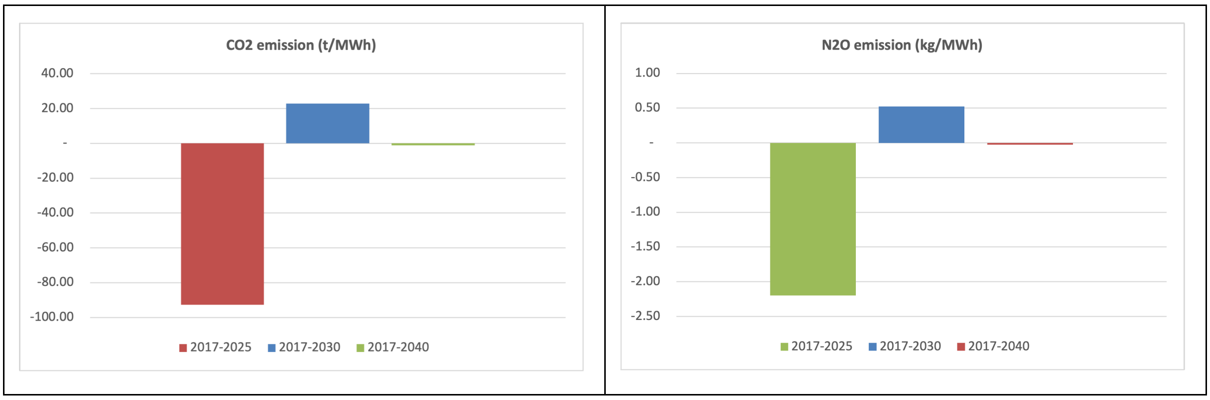


Figure 17. Production based emission reduction of 1 MWh of marginal electricity

In the scenarios of not updating the S matrix for future years, there is no difference in the obtained PBA results if we do or do not update future S matrices. Because from the production perspective, the model quantifies the air emissions of electricity generation based on ecoinvent data (process based LCI), which is independent from the IO equations. Meanwhile, there is a slight difference in the CBA results, in which the results obtained with updated S matrices is lower than those obtained without updating matrix S. The following sections will present the obtained results on air emission of marginal electricity with and without updating future S matrices.

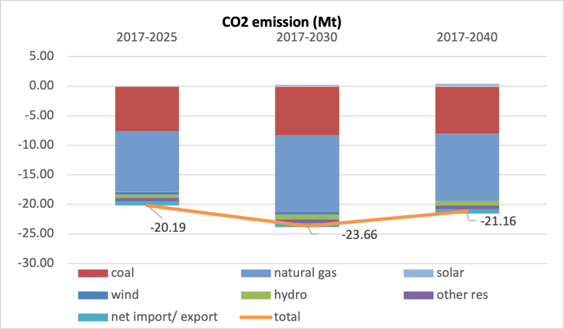
5.1.3. CBA of marginal Italian electricity with updated S matrix

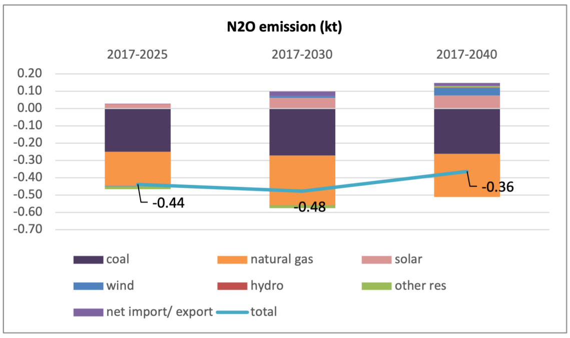
From the consumption perspective, the emissions of marginal electricity production and consumption reduces in six out of 10 air emission categories, except for CH_4, NH_3, NMVOC and CO during the period 2017-2040. In most of the cases, the emission reduction is at peak by 2030, and the emissions reduction of the period 2017-2025 and 2017-2040 is similar (for CO_2, N_2O, NOx, SOx, CO, PM_{10} and $PM_{2.5}$). For the case of CH_4, NH_3, NMVOC and CO, the emissions gradually increase between 2017-2040. The emissions of CO is negative (emission reduction benefit) in the periods of 2017-2025 and 2017-2030, but positive considering the whole period 2017-2040.

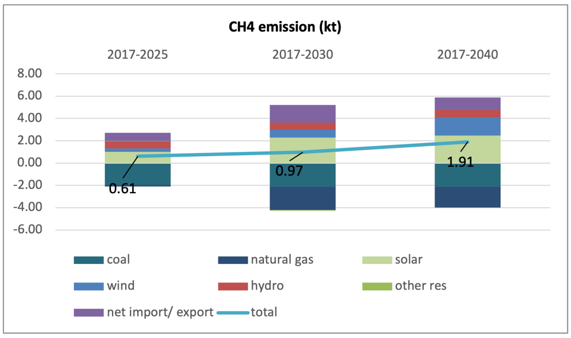
The emissions (reductions) are shared among electricity technologies. The large shares come from coal-based and natural-gas-based electricity. Shares of emissions from renewable electricity such as wind and solar are visible due to their emissions from infrastructure production. It should be noted that most of emission reduction comes from the coal-based and natural-gas-based electricity (thanks to the drop in fossil fuel consumption for electricity generation between 2017 and the future years), while the renewable electricity such as solar power and wind power release some certain amounts of emissions (due to the further investment into RE technologies).

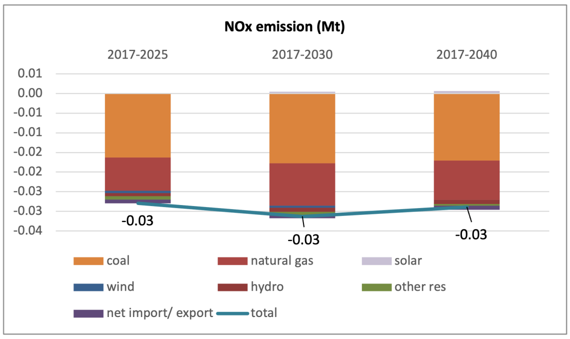
At the same time, the CBA emissions are lower than the PBA emissions in all air emission categories, because the CBA emissions indicate the emissions associated with all economic activities to meet the final demand on electricity. In such case, the CBA excludes a part of air emissions embodied in electricity used for manufacturing other final product. For example, there are air emissions from electricity consumption during the manufacture of transportation vehicles, which are accounted for the transportation equipment sector, not electricity sector.

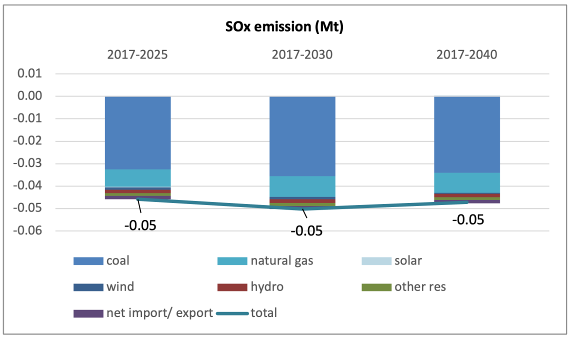
Specifically, the CO_2 emission reduction is at peak at 23.66 $MtCO_2$ in the period 2017-2030, while emission reductions of the period 2017-2025 and 2017-2040 are around 20~21 $MtCO_2$. Figure 18 presents the CBA air emissions of marginal electricity production and consumption during 2017-2040 for electricity sector.

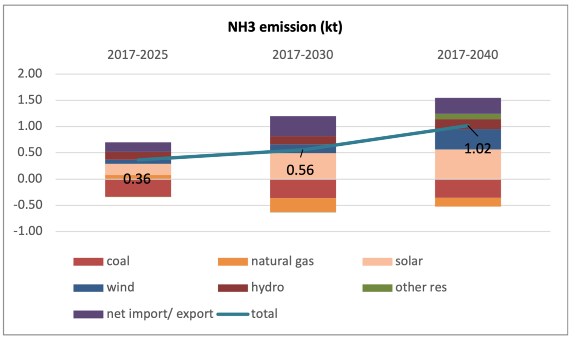

CO2 emission (Mt)

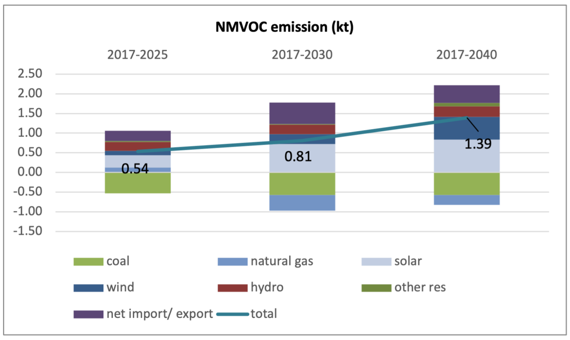

N2O emission (kt)

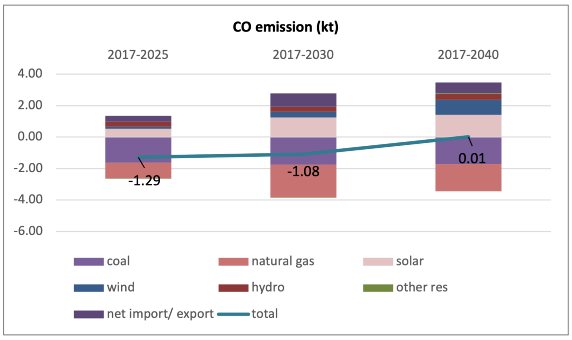

CH4 emission (kt)


NOx emission (Mt)


SOx emission (Mt)


NH3 emission (kt)


NMVOC emission (kt)


CO emission (kt)

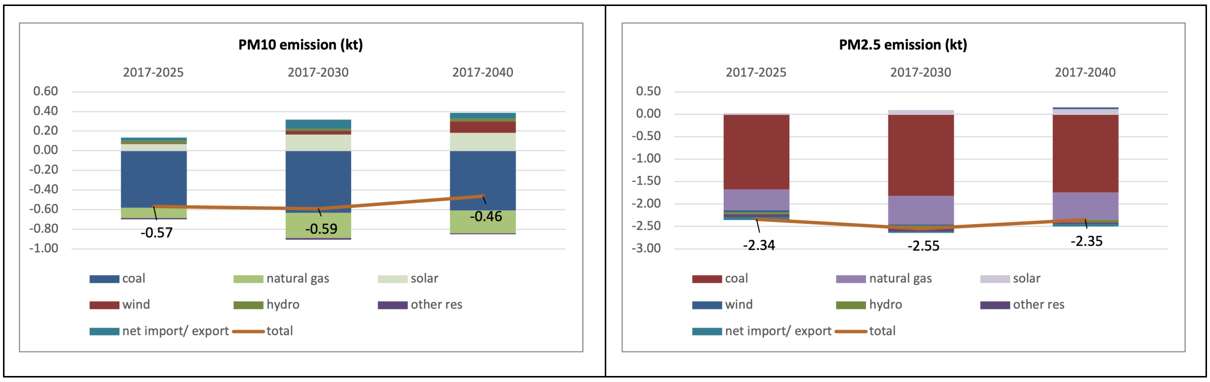


Figure 18. Consumption based emission reduction of electricity sectors

Per one MWh, there is a reduction trend in all air emissions categories. In the cases of emission reductions (for CO_2, N_2O, NOx, SOx, CO, PM_{10} and $PM_{2.5}$), the emission reductions gradually decrease along the years, which is due to the fact that the speed of increase in electricity generation overtakes the speed of decrease in emission reduction effort (through investing in renewable power). In contrast, the emission changes of CH_4, NH_3 and NMVOC are positive and decrease year by year, meaning that the speed of increase in electricity generation is lower than the speed of decrease in emission reduction effort. Figure 19 presents the CBA emissions of marginal electricity production and consumption during 2017-2040 per one MWh of electricity.

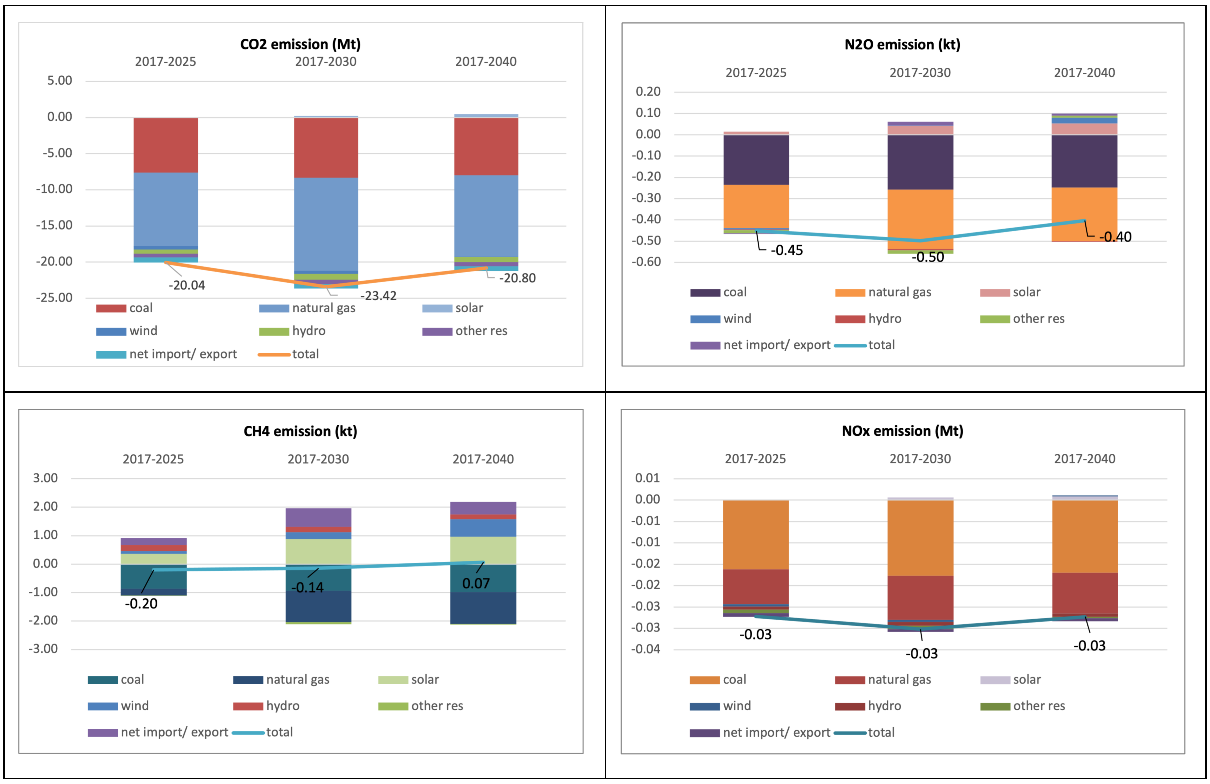
Figure 19. Consumption based emission reduction of 1 MWh of marginal electricity

5.1.4. CBA of marginal Italian electricity without updating S

Without updating the S matrix, from the consumption perspective, the emissions of marginal electricity production and consumption reduce in seven out of 10 air emission categories, except for CH_4, NH_3 and NMVOC during the period 2017-2040. In most of the cases, the emission reductions are at their peaks by 2030, and the emission reductions of the period 2017-2025 and 2017-2040 is similar (for CO_2, N_2O, NOx, SOx, CO, PM_{10} and $PM_{2.5}$). For the case of CH_4, NH_3 and NMVOC, the emissions of the whole period 2017-2040 is slightly higher than those of the period 2017-2025.

Figure 20 also indicates that emissions (reductions) are shared among electricity technologies, with most of the emission reductions coming from coal-based and natural-gas-based electricity, while RE technologies cause a certain amount of emissions. These patterns are similar to the results of updating S matrix in the previous section.

Specifically, the CO_2 emission reduction is at its peak, at 23.42 $MtCO_2$ in the period 2017-2030, while the emission reductions of the period 2017-2025 and 2017-2040 are around 20 $MtCO_2$. These emission reductions are slightly smaller than those of updating the S matrices. The change in CO_2 as well as other air emissions are presented in Figure 20.



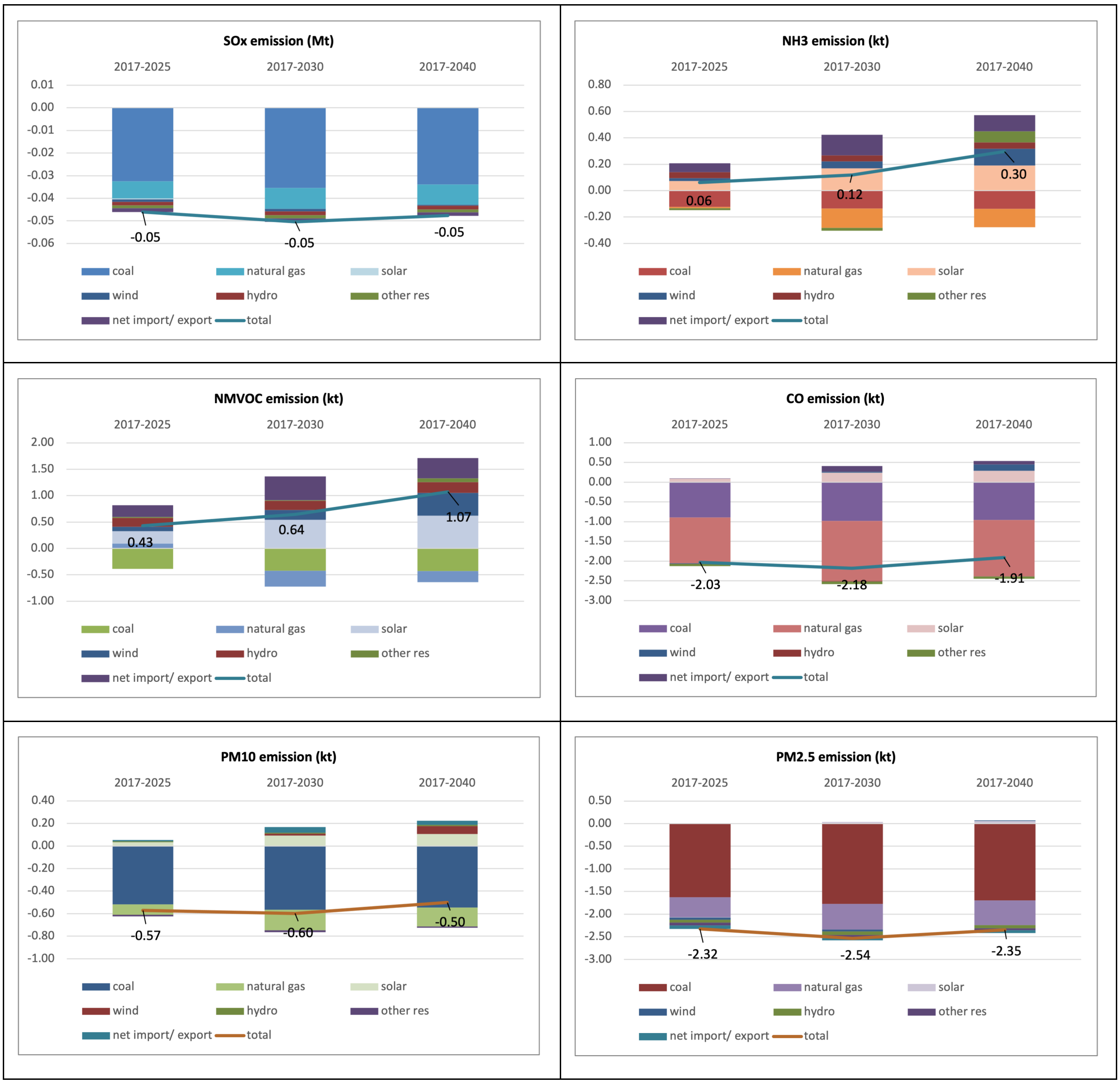


Figure 20. Consumption based emission reduction of electricity sectors without updating S matrix

Per MWh, there is a reduction trend in all air emission categories comparing three periods of 2017-2025, 2017-2030 and 2017-2040. In the cases of emission reductions (for CO_2, N_2O, NOx, SOx, CO, NMVOC, PM_{10}, $PM_{2.5}$), the emission reductions gradually decrease along these years, which is due to the fact that the speed of increase in electricity generation overtakes the speed of decrease in emission reduction effort (through investing in renewable power). In contrast, the emissions of NH_3 and NMVOC decrease along the years, meaning that the speed of increase in electricity generation is lower than the speed of decrease in emission reduction effort. These patterns are similar to those obtained without updating the S matrix. The only difference lies in CH_4 emissions, for which the periods of 2017-2025 and 2017-2030 see some emission reduction benefits, while the CH_4 emission increases for the whole period of 2017-2040. Meanwhile, there is no reduction benefit in CH_4 emissions in all periods 2017-

2025, 2017-2030 and 2017-2040. Figure 21 below presents air emission reductions per 1MWh, from consumption perspective, without updating S matrix.

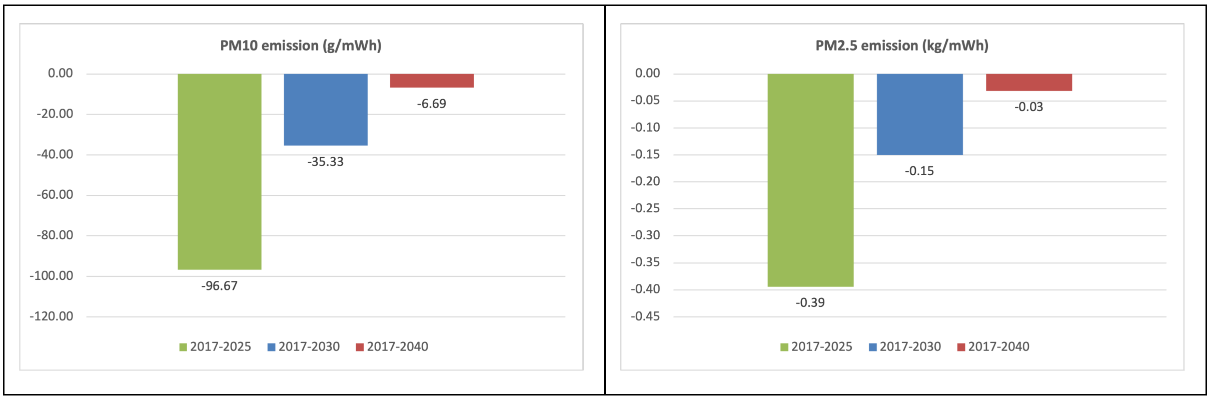


Figure 21. Consumption based emissions reduction of 1 MWh of marginal electricity without updating S matrix

Comparing the results obtained updating and not updating the S matrix, the emission reduction benefits are clearly shown in CH_4, NH_3 and CO (See Table 20, cells being highlighted in green). The electricity sector emits about 70 tonnes of CH_4 emissions by 2040 in case of no change in S matrix, as compared to 2.52 tonnes of CH_4 emission reduction by the same time in case of updating the S matrix. Meanwhile, it seems there is no difference in the SOx emission reduction benefits between updating and not updating matrix S. The difference in emission reduction benefits of CO_2, N_2O, NOx, and $PM_{2.5}$ emissions categories are small, ranging between 1% and 8% in various time periods. The difference in those of NH_3, NMVOC, CO and PM_{10} are relatively large, around 17-91% in various time periods. Similarly, the emission reduction benefits per one MWh in the scenario of updating S matrix are larger than those of the scenario without updating the S matrix. Table 20 shows the difference between obtained results with and without updating matrix S.

Table 20. Difference between consumption-based emissions reduction with and without updating S

	Unit	Updating S	Not updating S	Difference (absolute)	Difference (percentage)
2017-2025					
CO_2	Mt	-20.19	-20.04	-0.15	1%
N_2O	kt	-0.44	-0.45	0.01	-3%
CH_4	kt	0.61	-0.20	0.81	-403%
NOx	Mt	-0.03	-0.03	0.00	-7%

SOx	Mt	-0.05	-0.05	0.00	-8%
NH_3	kt	0.36	0.06	0.30	503%
NMVOC	kt	0.54	0.43	0.11	24%
CO	kt	-1.29	-2.03	0.74	-37%
PM_{10}	kt	-0.57	-0.57	0.00	-1%
$PM_{2.5}$	kt	-2.34	-2.32	-0.02	1%
2017-2030					
CO_2	Mt	-23.66	-23.42	-0.24	1%
N_2O	kt	-0.48	-0.50	0.02	-5%
CH_4	kt	0.97	-0.14	1.11	-789%
NOx	Mt	-0.03	-0.03	0.00	4%
SOx	Mt	-0.05	-0.05	0.00	0%
NH_3	kt	0.56	0.12	0.44	367%
NMVOC	kt	0.81	0.64	0.17	26%
CO	kt	-1.08	-2.18	1.10	-50%
PM_{10}	kt	-0.59	-0.60	0.01	-2%
$PM_{2.5}$	kt	-2.55	-2.54	-0.01	0%
2017-2040					
CO_2	Mt	-21.16	-20.80	-0.36	2%
N_2O	kt	-0.36	-0.40	0.04	-9%
CH_4	kt	1.91	0.07	1.84	2623%
NOx	Mt	-0.03	-0.03	0.00	-4%
SOx	Mt	-0.05	-0.05	0.00	-5%
NH_3	kt	1.02	0.30	0.72	241%

NMVOC	kt	1.39	1.07	0.32	30%
CO	kt	0.01	-1.91	1.92	-101%
PM_{10}	kt	-0.46	-0.50	0.04	-7%
$PM_{2.5}$	kt	-2.35	-2.35	0.00	0%

5.1.5. C-LCA impacts

C-LCA impacts was quantified with various life cycle impact assessment (LCIA) methodologies, including Intergovernmental Panel on Climate Change (IPCC) 100a, IPCC 20a, Recipe Midpoint H, CML, EDP and Traci. Because the numbers of NAMEA air emission are limited (in 10 air emissions), the C-LCA impact categories are quantified for some relevant impacts, including: Global warming potential (GWP) , Stratospheric ozone depletion (ODP), Ozone formation (Terrestrial ecosystems and Human health) (OFP, TES and OFP, HH), Photochemical oxidation (PCOP), Smog, Fine particulate matter formation (FPMF), Respiratory effect , and Human toxicity (HT).

It should be noted that some impact categories can be well quantified, for example GWP, because the GWP indicator can be well quantified with the emissions of main GHGs such as CO_2, CH_4 and N_2O. However, the study underestimates other impacts such as ozone depletion, human toxicity. The main cause of ozone depletion are emissions of HFC, CFC and other F-gases, which are not included in NAMEA tables. As a result, the ozone depletion impact of this study has neglected a considerable amount of impacts caused by F-gases. For the case of human toxicity, this impact is collectively relevant to emissions to air, water and soil. Meanwhile, the NAMEA tables only report emissions to air, which causes the underestimate of human toxicity in this study.

Table 21 presents the C-LCA impacts of one MWh of marginal electricity with and without updating S. There are no difference in the obtained results with different LCIA methodologies. For example, the GWPs per one MWh of marginal electricity by 2040 are -1.21 tCO_2eq and 0.28 tCO_2eq, with production and consumption perspectives, respectively, with all applicable LCIA methods of IPCC GWP 100a, IPCC GWP 20a, Recipe midpoint H GWP, CML GWP 100a, EDP GWP 100a and Traci GWP.

There are slightly difference in the results of updating and not updating S matrix (referred to cells highlighted in green in Table 21). For example the ODP impact of updating S matrix is -0.05 gCFC11 compared to -0.06 gCFC11 in case of not updating S. or the OFP impacts are 0.38 and 0.36 kg NOx in case of updating and not updating S matrix, respectively.

Table 21. C-CLA impacts of one MWh of marginal electricity

For Global Warming Potential

1 MWh of marginal Italian electricity	IPCC GWP 100a (tCO_2eq)	IPCC GWP 20a (tCO_2eq)	Recipe midpoint H GWP (tCO_2eq)	CML (GWP100a) (tCO_2eq)	EDP (GWP100a) (tCO_2eq)	Traci GWP (tCO_2eq)

PBA 2025	-93.28	-93.38	-93.36	-93.27	-93.27	-93.34
PBA 2030	22.98	23.00	23.00	22.98	22.98	23.00
PBA 2040	-1.21	-1.21	-1.21	-1.21	-1.21	-1.21
Updating S matrix						
CBA 2025	-3.44	-3.43	-3.44	-3.44	-3.44	-3.44
CBA 2030	-1.41	-1.40	-1.41	-1.41	-1.41	-1.41
CBA 2040	-0.28	-0.28	-0.28	-0.28	-0.28	-0.28
Not updating S matrix						
CBA 2025	-3.42	-3.42	-3.42	-3.42	-3.42	-3.42
CBA 2030	-1.40	-1.40	-1.40	-1.40	-1.40	-1.40
CBA 2040	-0.28	-0.28	-0.28	-0.28	-0.28	-0.28

For the ozone-related impacts

1 MWh of marginal Italian electricity	Recipe Stratospheric ozone depletion (g CFC_{11} eq)	Recipe Ozone formation, Terrestrial ecosystems (kg NOx eq)	Recipe Ozone formation, Human health (kg NOx eq)	CML Photochemical oxidation (g C_2H_4 eq)	EDP Photochemical oxidation (kg NMVOC)	Traci Smog (kg O_3 eq)
PBA 2025	-24.20	-124.63	-124.62	-273.48	-125.15	-3089.65
PBA 2030	5.72	29.40	29.40	63.66	29.52	728.96
PBA 2040	-0.33	-1.56	-1.56	-3.36	-1.57	-38.68
Updating S matrix						
CBA 2025	-0.82	-4.71	-4.72	-5.28	-4.66	-117.48
CBA 2030	-0.31	-1.84	-1.84	-1.38	-1.81	-45.91
CBA 2040	-0.05	-0.38	-0.38	0.16	-0.37	-9.56
Not updating S matrix						
CBA 2025	-0.84	-4.59	-4.60	-9.38	-4.55	-114.30
CBA 2030	-0.32	-1.78	-1.78	-3.56	-1.76	-44.38
CBA 2040	-0.06	-0.36	-0.36	-0.80	-0.35	-8.93

For acidification and eutrophication

1 MWh of marginal Italian electricity	Recipe Terrestrial acidification (kg SO_2 eq)	CML Acidification (kg SO_2 eq)	EDP Acidification (fate not incl.) (kg SO_2 eq)	Traci Acidification (kg SO_2 eq)	CML Eutrophication (kg PO_4--- eq)	EDP Eutrophication (kg PO_4--- eq)	Traci Eutrophication (kg N eq)
PBA 2025	-45.44	-62.78	-87.78	-87.78	-16.90	-16.90	-5.55
PBA 2030	10.71	14.80	20.70	20.70	3.98	3.98	1.31
PBA 2040	-0.56	-0.78	-1.09	-1.09	-0.21	-0.21	-0.07
Updating S matrix							
CBA 2025	-1.59	-2.27	-3.20	-3.20	-0.61	-0.61	-0.20
CBA 2030	-0.60	-0.87	-1.23	-1.23	-0.24	-0.24	-0.08
CBA 2040	-0.11	-0.17	-0.24	-0.24	-0.05	-0.05	-0.02
Not updating S matrix							
CBA 2025	-1.64	-2.29	-3.21	-3.21	-0.62	-0.62	-0.20
CBA 2030	-0.63	-0.88	-1.24	-1.24	-0.24	-0.24	-0.08
CBA 2040	-0.12	-0.17	-0.24	-0.24	-0.05	-0.05	-0.02

For the air quality impacts

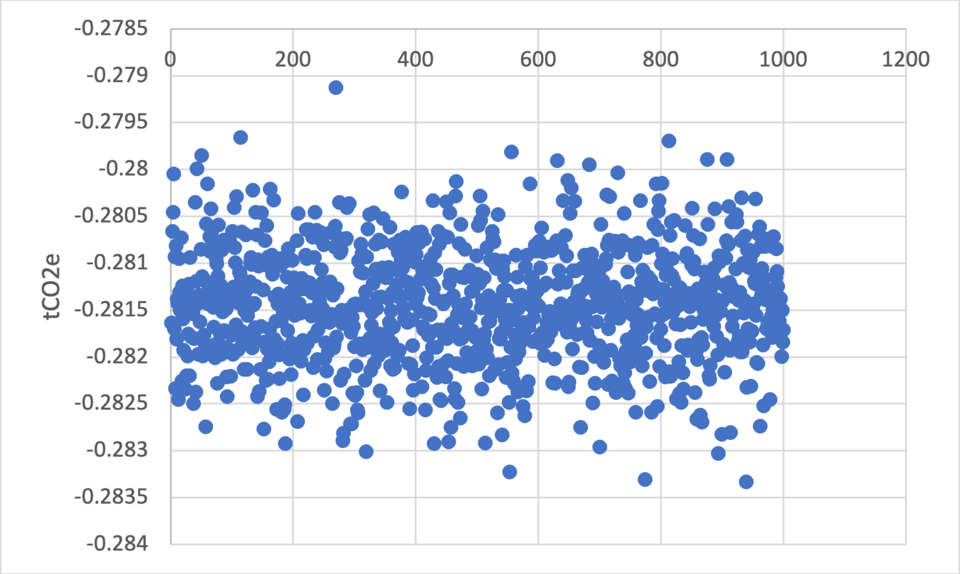
1 MWh of marginal Italian electricity	Recipe Fine particulate matter formation (kg $PM_{2.5}$ eq)	Traci Respiratory effects (kg $PM_{2.5}$ eq)	CML Human toxicity (kg 1,4-DB eq)
PBA 2025	-13.78	-3.32	-158.20
PBA 2030	3.25	0.78	37.30
PBA 2040	-0.17	-0.04	-1.98
Updating S matrix			
CBA 2025	-0.51	-0.12	-6.01
CBA 2030	-0.20	-0.05	-2.34
CBA 2040	-0.04	-0.01	-0.49
Not updating S matrix			
CBA 2025	-0.50	-0.12	-5.85
CBA 2030	-0.20	-0.05	-2.27
CBA 2040	-0.04	-0.01	-0.46

5.1.6. Uncertainty analysis

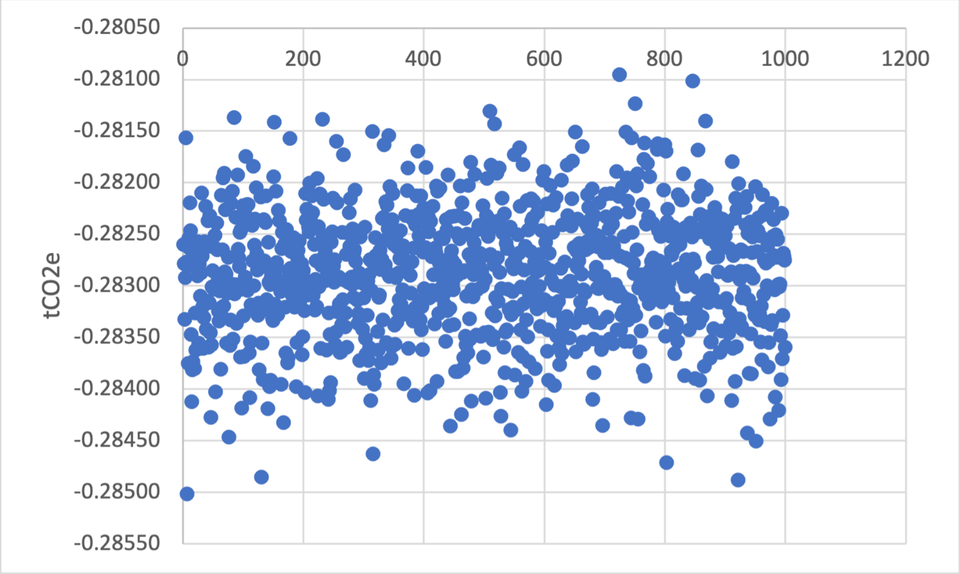
A Monte Carlo simulation has been conducted with 1000 runs for analysing the uncertainty of the GWP of 1MWh of marginal electricity by 2040 from consumption based perspective. It is found out that the GWP ranges from -0.284 to -0.28 tCO2e/MWh, with the mean value of -.0282 tCO_2e/MWh. In case of not updating the pollution coefficient matrix, the uncertainty analysis provide a similar results. Specifically, in case of without updating pollution coefficient matrix, the GWP ranges from -0.283 to -0.279 tCO2e/MWh, with the mean value of -.0281 tCO_2e/MWh The probability distribution of GWP of marginal electricity by 2040 is presented in Figure 22.

Figure 22. Probability distribution of GWP of 1 MWh of marginal electricity by 2040,

(a) With updating pollution coefficient matrix



(b) Without updating pollution coefficient matrix



5.2. Interactions among energy climate policy, energy power system and the economy.

5.2.1. Global air emissions

The global GHGs quantified with this model is 47.69 GtCO_2eq, which is slightly higher than the global GHG emissions estimated by the World Bank (WB), at 45.2 GtCO_2eq (WB, 2020)[19] or by CAIT model of Climate Watch, at 47 GtCO_2eq (Climate Watch, 2022)[20]. The difference in the obtained results of this model and other model such as CAIT is caused by the difference in scope of air emissions being studied. This model has been developed based on Istat database for Italy and EXIOBASE data for RoW. Both of Istat and EXIOBASE database are actual anthropogenic emissions of CO_2, CH_4 and N_2O, excluding emissions from LULUCF 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 LUCF. This causes a difference of around 1 GtCO_2eq of F-gases and 2.8 Gt CO_2eq of CH4. Moreover, Climate Watch's model excludes short-cycle biomass burning such as agricultural waste burning and savanna burning, but including other biomass burning such as forest fires, post-burn decay, peat fires and decay of drained peatlands. The exclusions 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 accounts up to 70% of the total GHG emissions (refer to Table 22). Moreover, this obtained results is very close to the reported number of IEA on CO_2 emissions for energy sector, at 32.92 GtCO_2e (IEA, 2022)[21]

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[19] WB's global GHG estimation is based on Climate Watch data. Available on: https://data.worldbank.org/indicator/EN.ATM.GHGT.KT.CE

For annex 1 only https://di.unfccc.int/time_series

[20] Calculated by CAIT model, excluding LUCF. Available on: https://www.climatewatchdata.org/ghg-emissions?end_year=2019&start_year=1990

[21] IEA, 2022, The global emissions of electricity sector. Available on:

Table 22 compares the global air emissions calculated by this model and other exiting model.

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https://www.iea.org/reports/greenhouse-gas-emissions-from-energy-overview/emissions-by-sector#abstract

and

https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser?country=WORLD&fuel=CO2%20emissions&indicator=TotCO2

Table 22. Comparison of global air emissions

	Unit	**This study** combustion only	**EXIOBASE** combustion only	**This study** all air emissions	**EXIOBASE** all air emissions	CAIT (excluding LUCF)	CAIT (including LUCF)	PIK (excluding LULUCF)	GAINS
CO_2	$GtCO_2eq$	32.31	32.27	34.33	34.30	34.70	35.70	35.40	
N_2O	$GtCO_2eq$	1.16	0.28	2.34	2.34	3.00	3.09	3.07	
CH_4	$GtCO_2eq$	0.42	0.47	11.02	11.01	8.25	8.33	7.80	
NOx	Mt	78.58	84.12	102.53	102.58	n/a	n/a	n/a	
SOx	Mt	75.70	69.90	110.39	110.23	n/a	n/a	n/a	
NH_3	Mt	15.46	15.10	83.83	83.95	n/a	n/a	n/a	
NMVOC	Mt	106.13	47.07	153.39	153.31	n/a	n/a	n/a	
CO_2	Mt	195.64	253.81	426.99	428.40	n/a	n/a	n/a	
PM_{10}	Mt	27.59	27.53	47.40	47.42	n/a	n/a	n/a	
$PM_{2.5}$	Mt	21.46	21.41	36.44	36.45	n/a	n/a	n/a	
F-gas	$GtCO_2eq$	n/a	n/a	n/a	n/a	1.09	1.09	0.99	
GHGs	$GtCO_2eq$	33.89	33.02	47.69	47.65	47.0	48.3	47.3	

https://data.worldbank.org/indicator/EN.ATM.PM25.MC.M3?view=chart

$PM_{2.5}$ emissions in 2017 (WB data): 46 microgram/m^3

5.2.2. Italian air emissions

At national level, there will be difference between production and consumption-based emissions, due to the difference in trade, import and export of the specific countries. In the case of Italy, the production-based GHG emissions in 2017 is 441.19 $MtCO_2e$, while that of consumption-based perspective is 510.77 $MtCO_2e$. Both the production and consumption-based GHG emissions is larger than the number reported to UNFCCC. The fourth Biannually Updated Report (BUR4) of Italy to UNFCCC[22] reported 427 $MtCO_2e$ (excluding LULUCF) and 409 $MtCO_2e$ (including LULUCF). Other air emissions of Italy, including 2.28 Mt and 3.16 Mt of CO (for production and consumption-based calculation, respectively); 0.92 Mt and 1.2 Mt of NMVOC; 0.37 Mt and 0.61 Mt of NH_3; 1.03 Mt and 1.11 Mt of NOx; 0.54 Mt and 0.8 Mt of SOx; 0.23 and 0.33 Mt of PM_{10}; and 0.2 Mt and 0.26 Mt of $PM_{2.5}$, is presented in the following Table 23.

The Italian production-based air emissions are slightly lower than the consumption-based ones in the air emissions of CO_2 and NOx, at around 7% or 8%. Regarding emissions of N_2O, NMVOC, CO, PM_{10} and $PM_{2.5}$, the difference between the production and consumption-based emissions ranges from 23% to 29%. Meanwhile the difference between production and consumption-based air emissions is largest among SOx, NH_3 and CH_4, ranging from 33% to 40%. While the production-based air emissions includes the emissions from production activities for domestic consumption (excluding export demand), the consumption-based air emissions includes emissions embodied in final consumption (either from domestic production, or import, excluding export), the difference between import and export (trade) causes the difference between the production and consumption-based emissions.

The lower CO_2 (and others) emissions from production-based perspective compared to consumption-based perspectives indicate Italian import is larger than those of export in term of economic value, or the emissions factors of import is larger than that of export.

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[22] Total GHG emissions of Italy in 2018: 399.6 $MtCO_2e$ (WB data); and 327.8 $MtCO_2e$, including 322.8 $MtCO_2e$ from fuel combustion (IEA data)

Table 23. Consumption and production-based accounting of Italy air emissions

Air emission	Unit	CBA		PBA		BUR excluding LULUCF	BUR including LULUCF	CAIT excluding LUCF	CAIT including LUCF	PIK excluding LULUCF	UNFCCC excluding LULUCF	UNFCCC including LULUCF
		This study	EXIOBASE	This study	EXIOBASE							
CO_2	$MtCO_2eq$	409.16	436.55	376.71	346.55	348.99	328.64	329.19	316.37			
N_2O	$MtCO_2eq$	21.28	24.90	16.49	13.08	17.80	18.29	16.18	16.21			
CH_4	$MtCO_2eq$	80.32	134.56	47.98	52.53	43.85	45.33	44.72	44.88			
NOx	Mt	1.11	1.45	1.03	1.08							
SOx	Mt	0.80	0.91	0.54	0.38							
NH_3	Mt	0.61	0.94	0.37	0.49							
NMVOC	Mt	1.20	1.01	0.92	0.84							
CO	Mt	3.16	4.41	2.28	3.69							
PM_{10}	Mt	0.33	0.36	0.23	0.24							
$PM_{2.5}$	Mt	0.26	0.30	0.20	0.21							
F-gases	Mt					17.07	17.07	14.28	14.28			
GHG	**$MtCO_2eq$**	**510.77**	**596.01**	**441.19**	**412.16**	**427.71**	**409.33**	**404.50**	**391.74**	**434.00**	**432.71**	**412.37**

Calculation in BUR report, CAIT model, PIK model and UNFCCC report follow sectorial approach, production based perspective.

Calculation in this study and EXIOBASE follows both the production and consumption based perspective.

https://www.climatewatchdata.org/ghg-emissions?end_year=2019&regions=ITA&source=CAIT&start_year=1990

Without considering the international trade, the production and consumption-based emissions[23] of Italy is 327.99 and 397.57 $MtCO_2eq$, respectively. The GHGs and other air emissions of Italy according to production and consumption perspectives, without considering the international trade are presented in Table 24.

Table 24. Italy CBA and PBA emissions without trade activities

All air emissions	Unit	PBA by region	CBA by region	Difference (absolute)	Difference (percent)
CO_2	$MtCO_2eq$	268.37	300.81	32.45	11%
N_2O	$MtCO_2eq$	14.67	19.47	4.80	25%
CH_4	$MtCO_2eq$	44.95	77.28	32.33	42%
NOx	Mt	0.84	0.92	0.08	8%
SOx	Mt	0.53	0.79	0.26	33%
NH_3	Mt	0.37	0.60	0.23	39%
NMVOC	Mt	0.54	0.83	0.29	35%
CO	Mt	0.43	1.30	0.88	67%
PM_{10}	Mt	0.10	0.20	0.10	48%
$PM_{2.5}$	Mt	0.08	0.14	0.06	42%
GHGs	$MtCO_2eq$	327.99	397.57	69.58	18%

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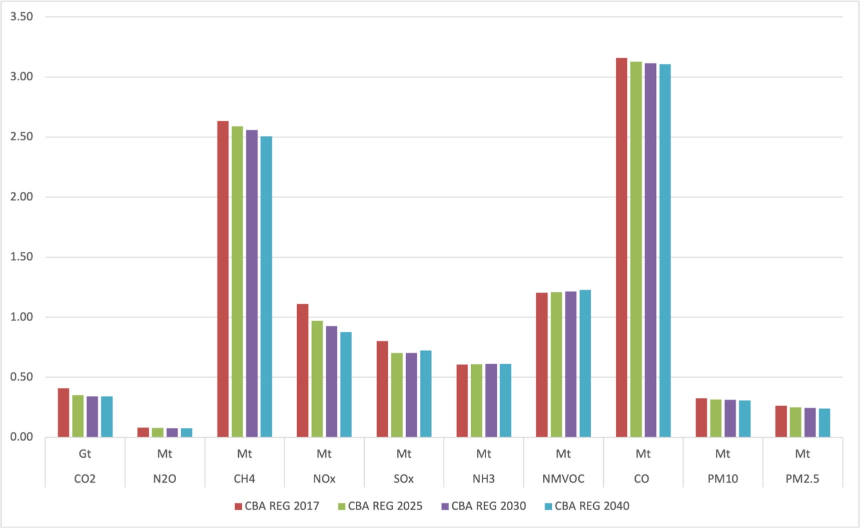
[23] CBA + Export – Import = CBA by region; PBA + Export – Import = PBA by region

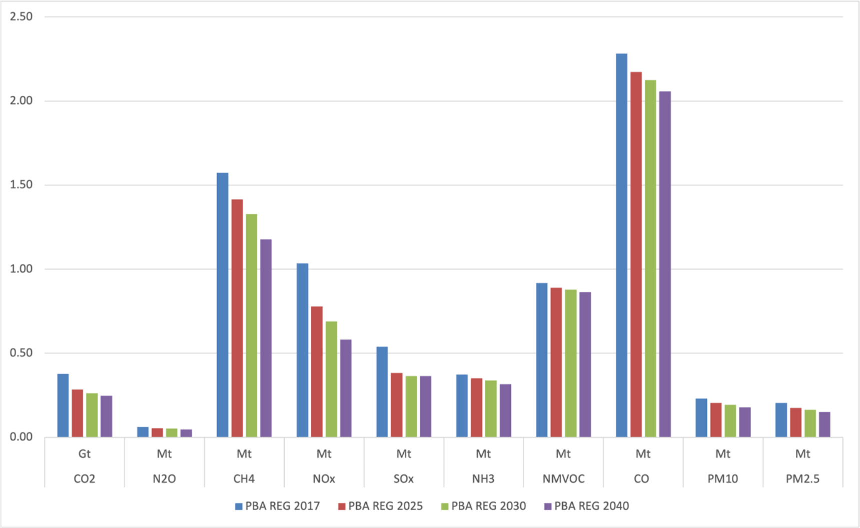
5.2.3. Air emission trends between 2017 and 2040

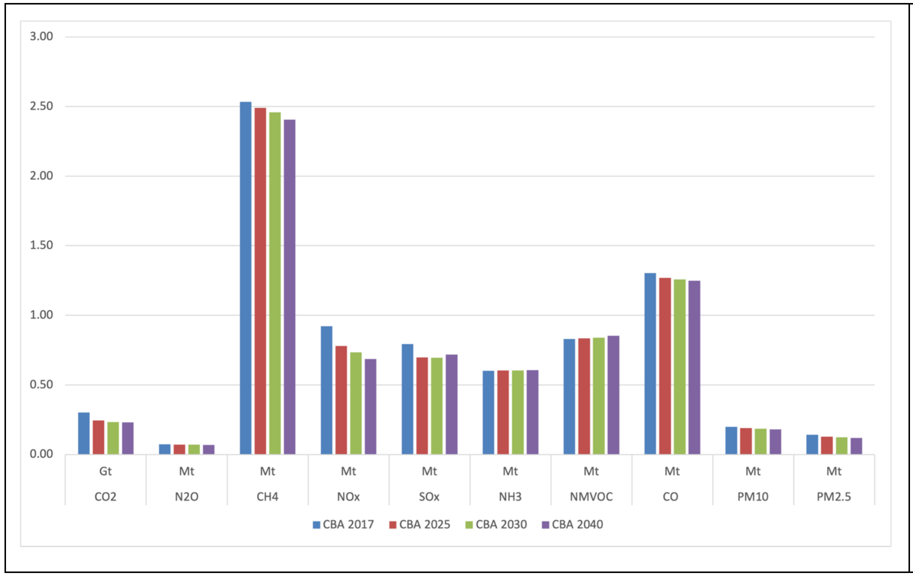
There is a difference in emission trends between production and consumption-based analysis during the period of 2017-2040. The Italian emissions tend to reduce during the period 2017-2040 in all air emission categories, considering the production-based emissions. Meanwhile, from the consumption-based perspective, the general trend is the decrease in most air emission categories, except for NH_3 and NMVOC during the same period. Figure 23 presents the change in air emissions over the period 2017-2040 from production and consumption perspective, in absolute value and in percentage.

From the production perspective, the emissions sharply reduce between 2017 and 2025, thanks to the transformational change in energy sector of phasing out coal in the electricity supply. The periods of 2025-2030 and 2030-2040 also see the emission reductions, but in much slower speed compared to the emission reductions between 2017 and 2025. For the whole period of 2017-2040, the emission reductions are obviously shown in CO_2, NOx and PM emissions. Specifically the emission of CO_2 reduces by 47.9%, and that of NOx reduces up to 53.8%. The emissions of PMs reduce by 50.3% and 64.4% in PM_{10} and $PM_{2.5}$, respectively. However, for the period of 2017 and 2025, the emission reductions are only clearly shown in CO_2 (34%), NOx (30.4%) and $PM_{2.5}$ (35.3%). The emission reductions of SOx and PM_{10} are around 29.4% and 24.3%. If we look at the sharply change of electricity sector between 2017 and 2025, and between 2017 and 2040, and considering the difference rates of emission reductions during these periods, we may conclude that the emission reductions of CO_2, NOx and SOx are closely related to the decarbonization of electricity sector. While the sharp reductions of CO and PMs between 2017 and 2040 are loosely linked to the decarbonization of electricity sector (refer to Figure 23).

In absolute values






3.00
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Gt
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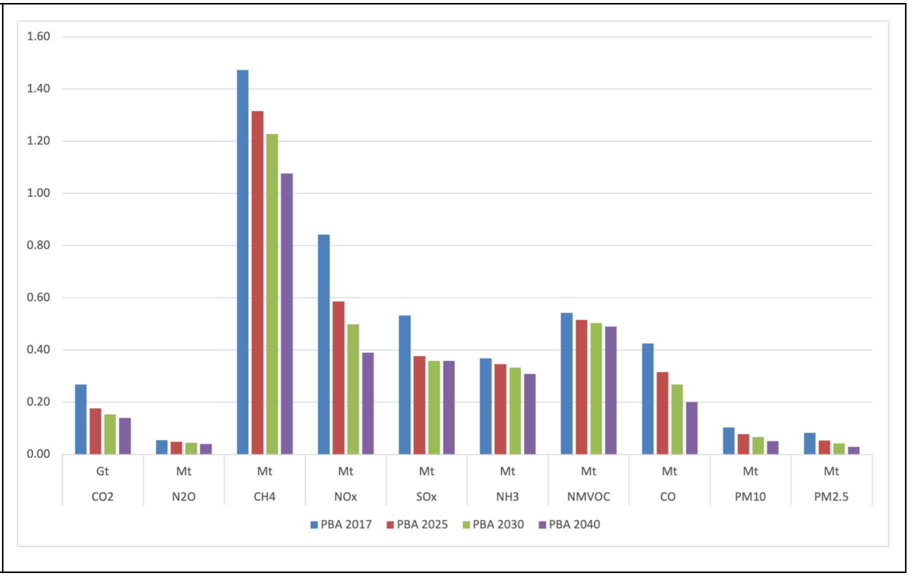
CBA 2017
CBA 2025
CBA 2030
CBA 2040


1.60
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SOx
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NH3
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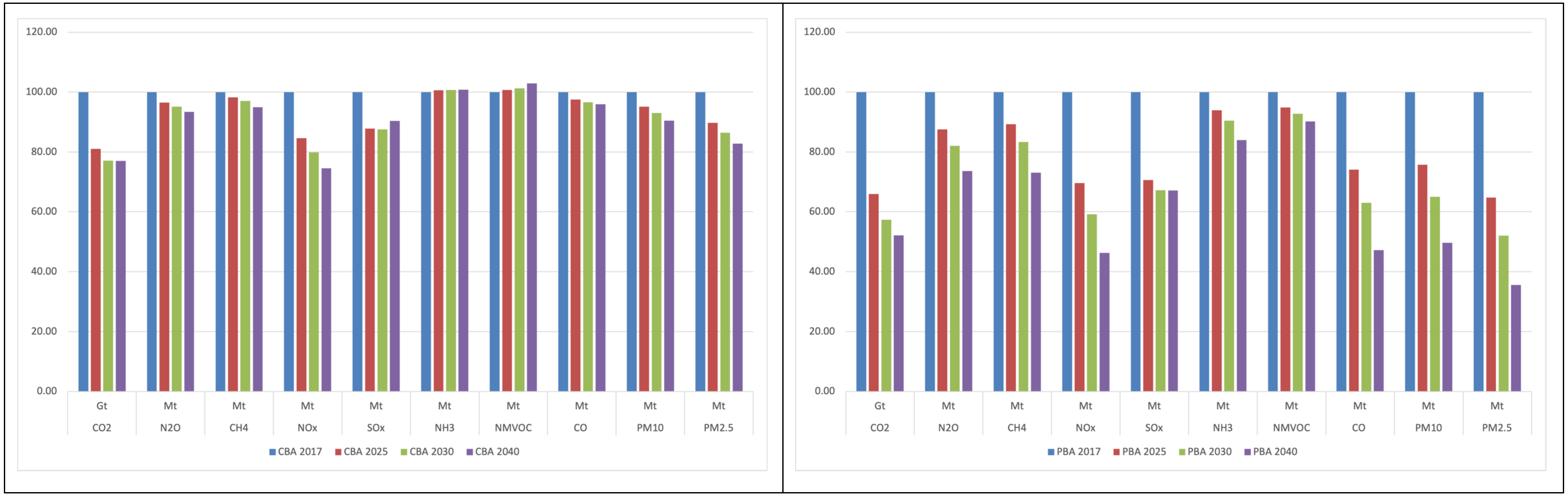
PBA 2017
PBA 2025
PBA 2030
PBA 2040

In percentage



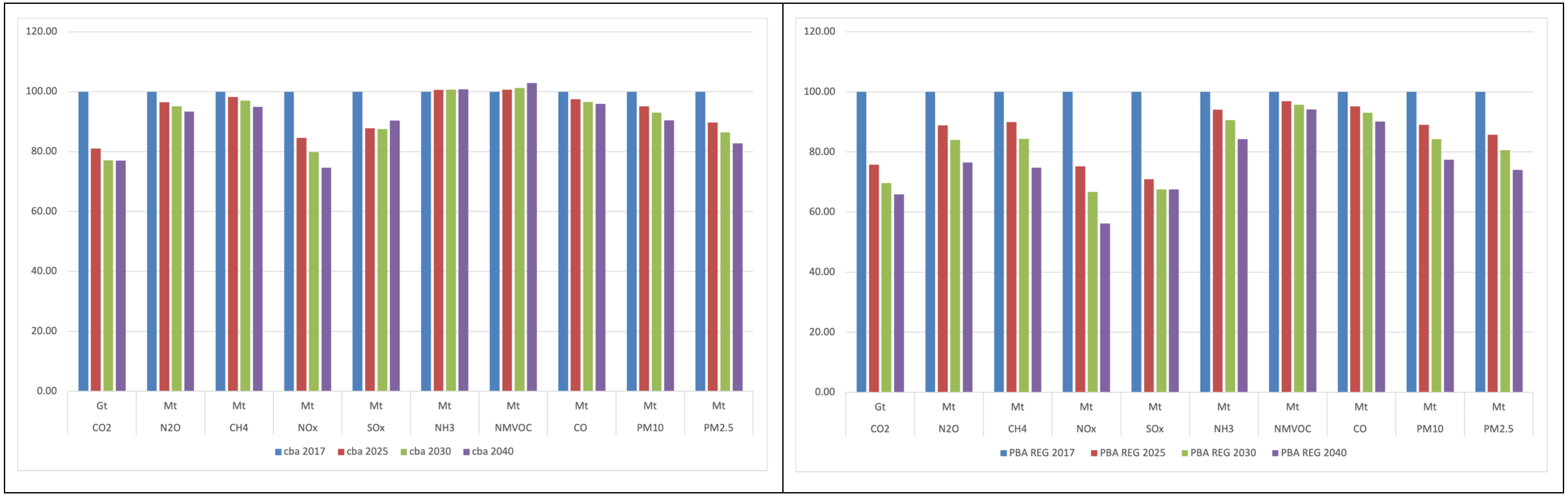


Figure 23. Comparison of four scenarios

The emission reductions from the consumption perspective shared the same trend as those from the production perspective, but at slower pace. For the whole period of 2017-2040, the emission reduction is obviously shown in CO_2 (reduction by 23%), NOx (reduction by 25.4%) and $PM_{2.5}$ emissions (reduction by 17.3%). Meanwhile for the period of 2017 and 2025, the emission reductions are clearly shown in CO_2 (19%), NOx (15.4%), SOx (12.2%), and $PM_{2.5}$ (10.3%).

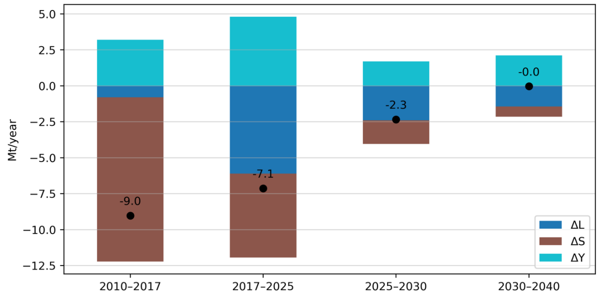
It should be noted that from consumption perspective, the emissions of NH_3 and NMVOC slightly increase during the period of 2017-2040. This could be explained that the increased emissions from the growth in final demand overtakes the emission reduction efforts of decarbonizing the electricity sector. Furthermore, it could be concluded that the decarbonization of the electricity sector insignificantly contributes to the reduction of NH_3 and NMVOC (less than its contribution to the GHGs, NOx, and SOx emission reductions).

5.2.4. Decomposition of air emission changes

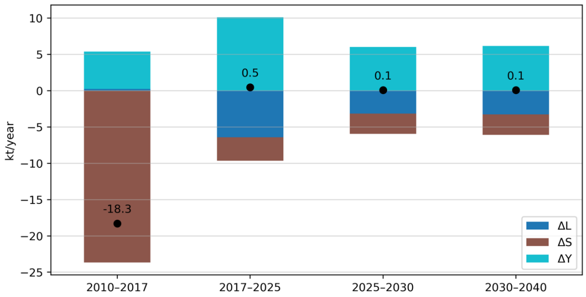
In order to look into details of the sources of the change in the air emissions, a decomposition analysis has been conducted following the study of (Dietzenbacher and Los, 1998). A similar study on air emission change of the Italian household consumption during 1999 and 2006 shows that, between 1999 and 2006, the indirect CO_2 emission from Italian household consumption was about 13 $MtCO_2$ (Cellura et al., 2012).

With the changes in the final demand and the electricity sector composition of Italy, consumption-based GHG emissions decrease in the period 2010-2040 (Figure 24). Specifically, due to the changes in the production structure, emission coefficients, and final demand, the annual CO_2 emission reduction embodied in production activities during 2010- 2017 was 12.5 $MtCO_2$. During the period 2017- 2025, the annual CO_2 emission reduction will be up to 7.1 $MtCO_2$, which makes up 57.1 $MtCO_2$ emission reduction at total, for 8 years of this period. The increased final demand of Italy causes an annual increase of 4.8 $MtCO_2$. While the change in production structure, including electricity sector and corresponding change in other economic sectors, helps to reduce 6.1 $MtCO_2$ annually. The change in emission flows coefficient 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.

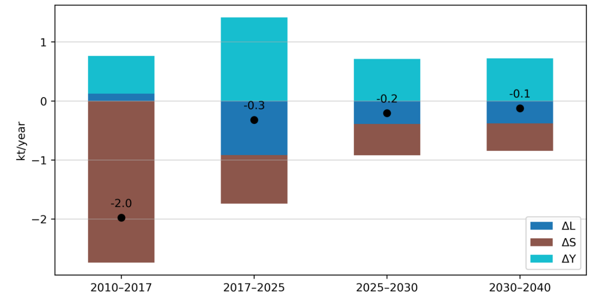
CO2: carbon dioxide (without biomass used as fuel)



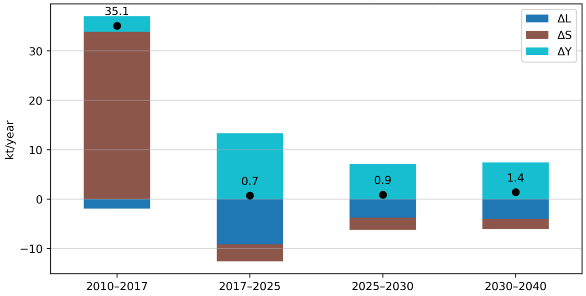
NH3: ammonia



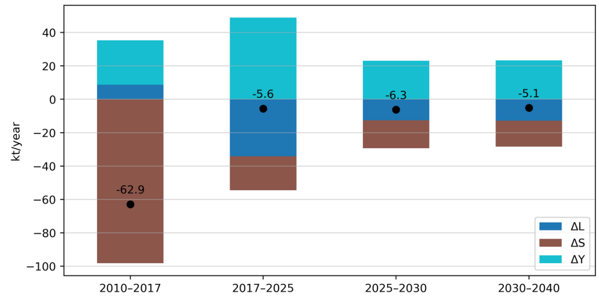
N2O: nitrous oxide



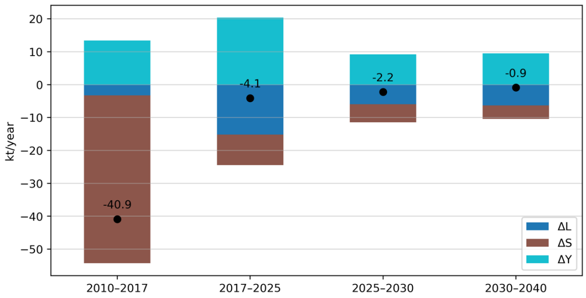
COVNM: non-methane volatile organic compounds



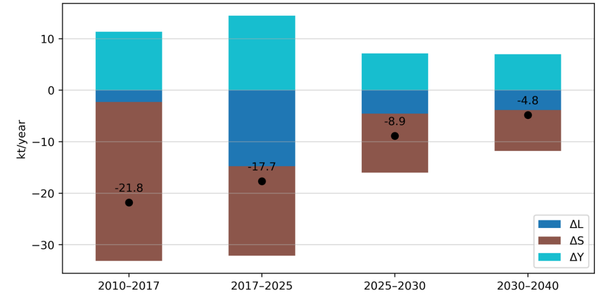
CH4: methane



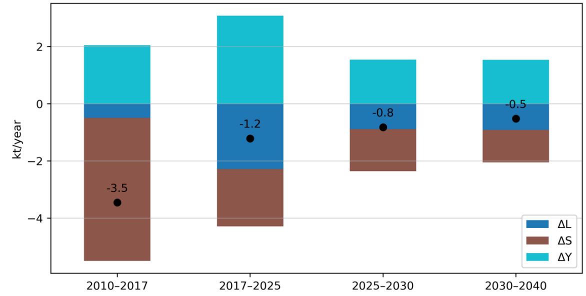
CO: carbon monoxide



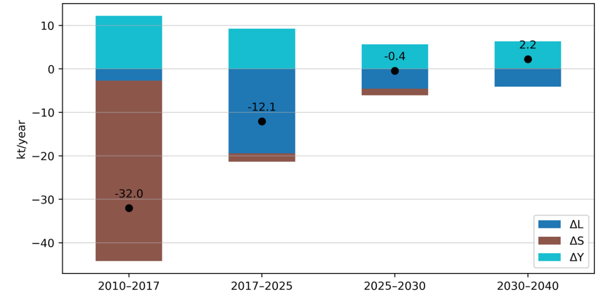
NOX: nitrogen oxides



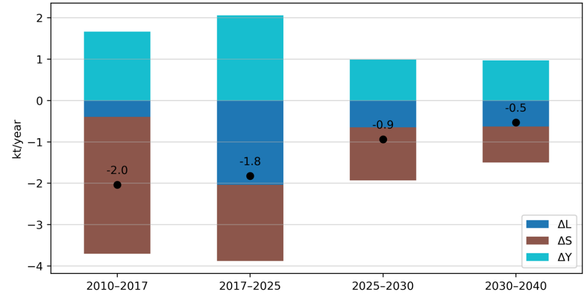
PM10: particulate matter



SOX: sulphur oxides



PM2_5: fine particulate



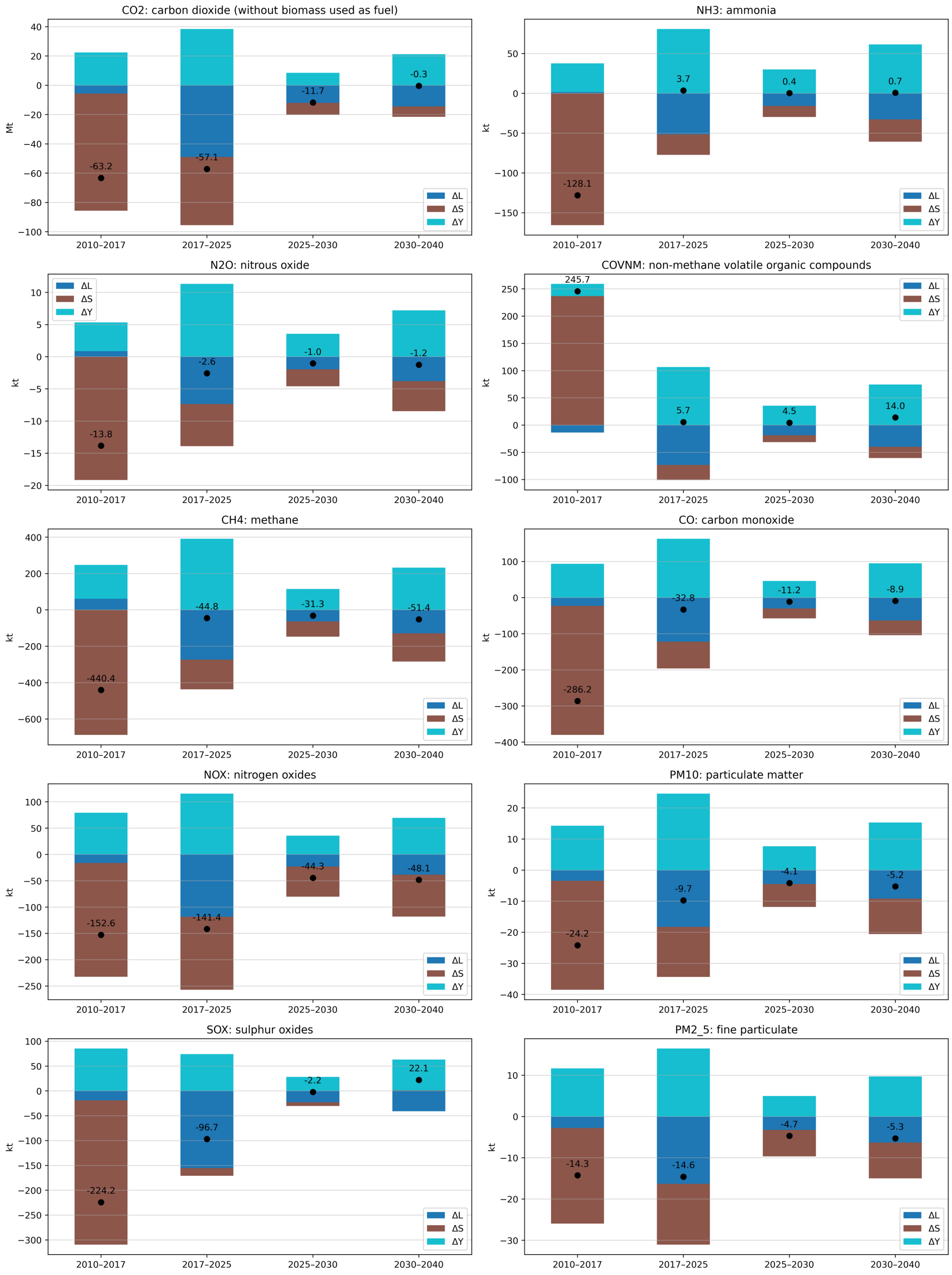


Figure 24. Decomposition of the Italian consumption-based emission variation over four periods annually (above) and for each period (below)

5.2.5. Identification of hot-spot sectors

There is a difference in 'hotspot' sectors when they are identified from production and consumption-based perspectives. From the production-based perspective, the 'hotspot' sectors include electricity, rubber and plastics, water transportation and agriculture, forestry and fishing sectors. For CO_2 emission, the electricity sectors accounts up to 36% total emissions of 2017. In the same year, the majority of other GHGs and NH_3 emissions comes from agriculture, forestry and fishing with 70% of N_2O, 53% of CH_4 and 97% of NH_3. For NOx, SOx, PM_{10} and $PM_{2.5}$, the emissions mostly come from water transportation, contributing up to 40%, 52%, 37% and 46% respectively. For CO emission, 29% comes from metals sector and another 25% from agriculture, forestry and fishing.

Meanwhile, from consumption-based perspective, apart from trade activities (import and export), four 'hotspot' sectors of wholesale and retail trade, agriculture, forestry and fishing, food and beverage, water transportation can be identified. Trade balance accounts for the largest part of all air emission categories, from 19% to 37%. Apart from trade activities, the agriculture, forestry and fishing sector contributes 14% of N_2O, 8% of CH_4 and 16% of NH_3, ranking first among the top contribution of N_2O and NH_3. Food manufacturing ranks first among the top contribution of CH_4, at 9%; and second among the top contribution of N_2O (12%), NH_3 (13%) and CO (6%). Water transportation is the large contributor for NOx, SOx and PM emissions, up to 13% of NOx, 12% of SOx, 7% of PM_{10} and 9% of $PM_{2.5}$. Wholesale and retail trade is the top contributor of CO_2, CO and PM_{10}, and holds a large share of air emissions in four emission categories such as NOx, SOx, NMVOC and $PM_{2.5}$, around 8% and 9%. Table 25 presents hotspot sectors identified with production and consumption based perspectives for different air emissions.

Table 25. List of hotspot sectors, PBA and CBA, for different air emissions

	PBA	CBA
CO_2	Electricity, rubber and plastics, water transport, coke and petroleum	Trade, wholesale and retail trade, construction, electricity (natural gas), health
N_2O	Agriculture, forestry and fishing, water and waste management, health, rubber and plastics and electricity	Trade, Agriculture, forestry and fishing, food and beverages, wholesale and retail trade, accommodation and food service

CH_4	Agriculture, forestry and fishing, water and waste management, food and beverages, chemicals, mining and quarrying	Trade, food and beverages, agriculture, forestry and fishing, water and waste management, wholesale and retail trade
NOx	Water transport, agriculture, forestry and fishing, electricity, land transport, rubber and plastics	Trade, water transport, wholesale and retail trade, construction, food and beverages
SOx	Water transport, electricity, coke and petroleum, rubber and plastics, metals	Trade, water transport, wholesale and retail trade, electricity (coal), construction
NH_3	Agriculture, forestry and fishing, water and waste management, electricity (other res) rubber and plastics, chemicals	Trade, agriculture, forestry and fishing, food and beverages, wholesale and retail trade, accommodation and food service
NMVOC	Agriculture, forestry and fishing, Construction, metals, wholesale and retail trade, textiles and leather	Trade, construction, wholesale and retail trade, food and beverages, agriculture, forestry and fishing
CO	Metals, agriculture, forestry and fishing, water transport, chemicals, rubber and plastics	Trade, wholesale and retail trade, food and beverages, construction, health
PM_{10}	Water transport, agriculture, forestry and fishing, rubber and plastics, metals and land transport	Trade, wholesale and retail trade, water transport, food and beverages, construction
$PM_{2.5}$	Water transport, agriculture, forestry and fishing, electricity, rubber and plastics, metals	Trade, water transport, wholesale and retail trade, construction, food and beverages

Contributions of economic sectors to the life cycle CO_2 emissions are visualized in Figure 25**Error! Not a valid bookmark self-reference.**.

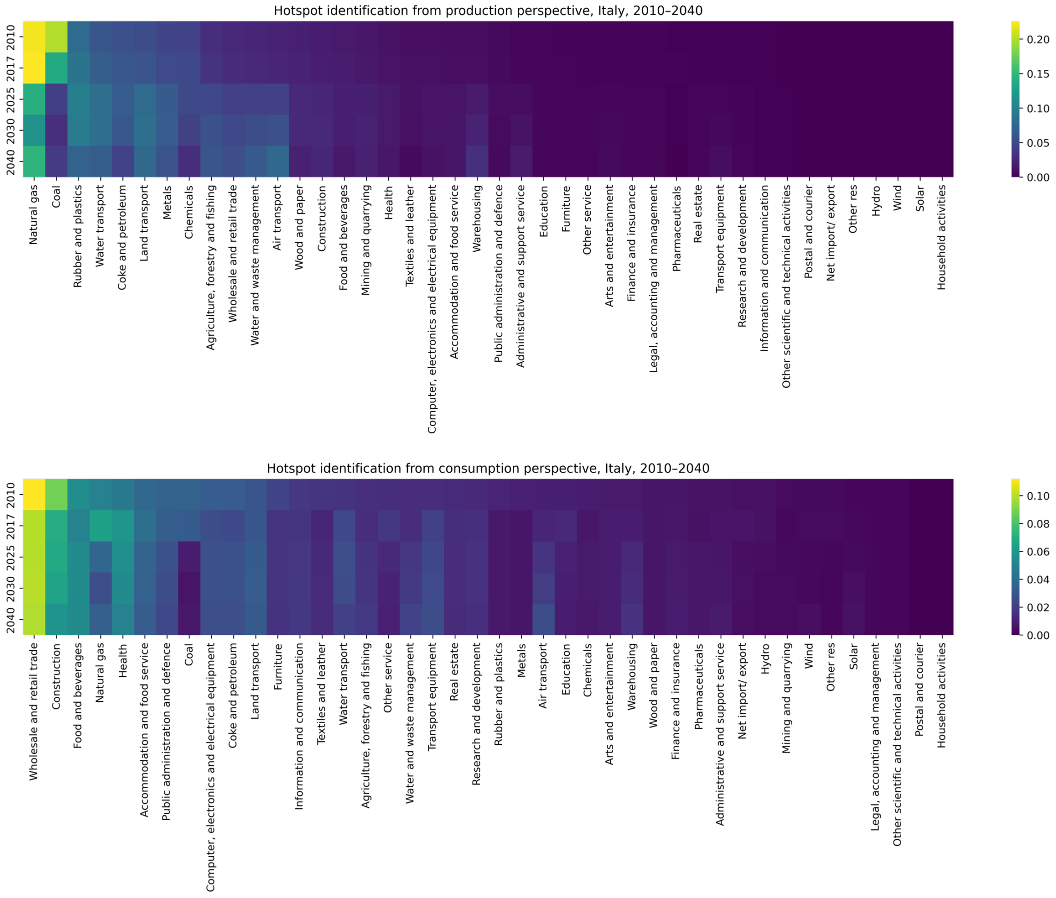


Figure 25. Hotspot identification in CO_2 emission from different perspectives

5.2.6. Change in air emissions in electricity sector

The hybridization of the electricity development scenario causes a change in all air emissions categories in 2017, at various scales. The smallest difference occurs in CO_2, at 8% of difference. The largest difference occurs in $PM_{2.5}$, which is followed by SOx. The difference in other air emissions of N_2O, CH_4, NOx, NH_3, NMVOC, PM_{10} ranges between -0.98 to 2.28. This difference is mainly caused by the level of aggregation of process-based LCI and IO data. IO data is taken from NAMEA, which reports air emissions of the electricity, gas and steam sector, while LCI data only includes air emissions of electricity supply technologies. First, this mismatch causes a missing 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 (Roman-White et al., 2021); therefore, the missing of emissions from *gas supply* in the LCI data will omit an amount of CH_4 emissions from this subsector, which explain the lower CH_4 emissions of hybrid results compared to the original NAMEA. Second, the air emissions of electricity supply technologies in LCI data is taken for the 'representative' technologies, or seven technologies contributing for the largest parts of the electricity supply in this study. In practice, the numbers of 'actual' power technologies go beyond seven technologies. The emissions are not the same for 'representative' and 'actual' technologies, which cause a difference between the hybrid results and the original IO data.

With the change in power supply technologies and power consumption, the emissions dramatically change in electricity sector. After 2017, due to the changes in power supply technologies and power consumption, the future air emissions dramatically reduce in the electricity sector, as presented in Figure 26. In 2017, from the production perspective, the electricity sector emits 97.5 $MtCO_2$ and 98.2 $MtCO_2e$ of GHGs. By 2040, this sector's emissions reduce to 25.9 $MtCO_2$ and 26.1 $MtCO_2e$ of GHGs (see also Table 26). This also occurs in all other non-GHG air emission categories, such as NOx, SOx, CO, NMVOC, CO, PM_{10} and $PM_{2.5}$. The reductions are sharp in CO_2, N_2O, CH_4, NOx, SOx, CO, PM_{10} and $PM_{2.5}$, at around 60% of reduction, while the reduction in NH_3 and NMVOC are much slighter at 5% between 2017 and 2040 (see also Table 26).

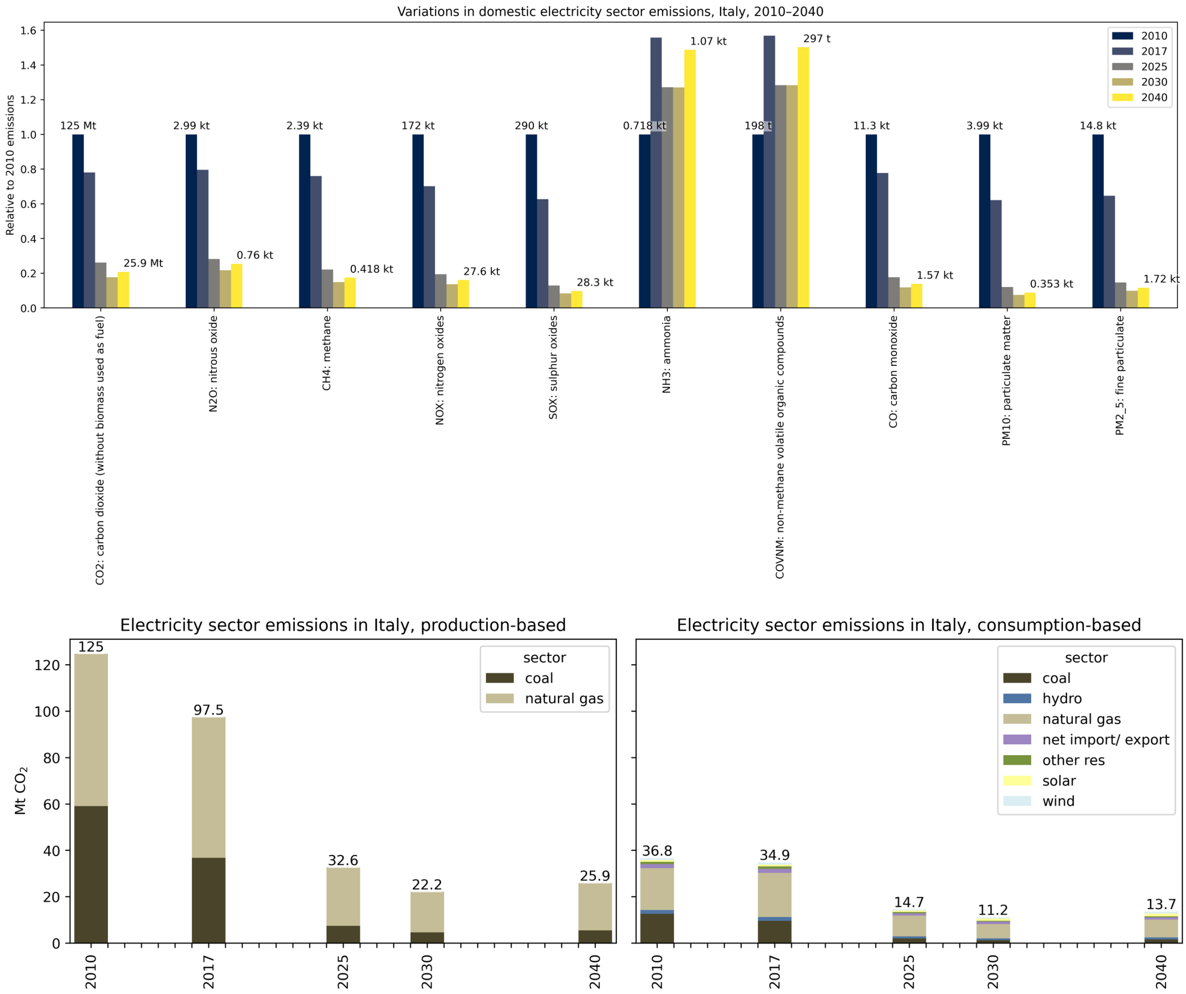


Figure 26. Emissions of electricity sectors for all air emissions (above) and for CO_2 emission (below)

Table 26. Air emissions of electricity sector by years

Air emissions	Unit	2010	2017	2025	2030	2040
CO_2	Mt	124.80	97.49	32.64	22.15	25.93
N_2O	kt	2.99	2.38	0.84	0.65	0.76
CH_4	kt	2.39	1.82	0.53	0.36	0.42
NOx	Mt	0.17	0.12	0.03	0.02	0.03
SOx	Mt	0.29	0.18	0.04	0.02	0.03
NH_3	kt	0.72	1.12	0.91	0.91	1.07
NMVOC	kt	0.20	0.31	0.25	0.25	0.30
CO	kt	11.32	8.80	2.00	1.34	1.57
PM_{10}	kt	3.99	2.48	0.48	0.30	0.35
$PM_{2.5}$	kt	14.76	9.54	2.17	1.47	1.72
GHGs	Mt	125.67	98.18	32.88	22.33	26.14

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 productions of solar and wind power do not generate any air-borne emission, while the operation of hydropower plant generate an amount of N_2O emission. The reductions in the electricity generated by fossil fuels such as coal and natural gas help to reduce the PBA emissions of this sectors nearly four times from 97.5 $MtCO_2$ in 2017 to 25.9 $MtCO_2$ by 2040. With regards on CBA, the CO_2 emission is 34.8 $MtCO_2$ in 2017, which reduces by more than half, at 13.6 $MtCO_2$ 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 their manufacturing of their infrastructures (see Figure 26).

Considering the whole economy, the difference between the production and consumption-based emissions is not large. For example the difference in CO_2 emission is at around 8% including trade balance and 10% excluding trade balance (refer to the previous section on Italian air emissions). However, considering one economic sector, there is a significant difference between production and consumption-based accounting. For example, the CO_2 emissions of the electricity sector in 2017, counted with production perspective nearly triples those counted with consumption perspective in the same year (see Figure 26). This is due to the difference in the quantification principles of the these two approaches. Production based emissions of one economic sector are emissions associated with that corresponding sector. In the case of the electricity sector, they are the direct emissions from the electricity generation processes. Meanwhile, the consumption-based emissions of one economic sector are emissions associated with all economic sectors to meet the final demand of that corresponding sector. In the case of the electricity sector, they includes emissions of the whole economy to meet final demand on electricity. In such case, the emissions of the electricity sector, which are accounted based on consumption perspective, excludes the emissions of electricity consumption for the final demand of other economic sectors, for example emissions from electricity consumption to meet final demand of cement sector.

Comparing the emissions of the electricity sector obtained in this study with emissions from fossil fuel consumption quantified by IEA or reported in the Italian BUR, it is identified that the GHG emissions of electricity sector account for around one third of emissions from fossil fuel combustion (see

Table 27).

Table 27. Air emissions of electricity and energy sector in 2017 by years

Air emissions	Unit	This study (electricity sector)	IEA (fossil fuel combustion)	BUR (fuel combustion)	GCP (fossil fuels and cement)
CO_2	$MtCO_2eq$	97.49	0	331.09	0
N_2O	$MtCO_2eq$	0.63	0	3.98	0
CH_4	$MtCO_2eq$	0.06	0	3.78	0
NOx	Mt	0.12	0	0	0
SOx	Mt	0.18	0	0	0
NH_3	Mt	0.00	0	0	0
NMVOC	Mt	0.00	0	0	0
CO	Mt	0.01	0	0	0
PM_{10}	Mt	0.00	0	0	0
$PM_{2.5}$	Mt	0.01	0	0	0
GHGs	Mt	98.18	327.2	338.84	352.85

https://www.iea.org/reports/greenhouse-gas-emissions-from-energy-overview/data-explorer

5.2.7. *Change in air emissions of other economic sectors*

The absolute change in air emissions of the electricity sector induces a change in the economy emission structure, as presented in Figure 27. In 2017, from production perspective, the Italian electricity sector accounts for the largest shares of the national emission of CO_2 (36%), which reduce 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 percent points each between 2017 and 2040. Some economic sectors, which have the smaller change in their share of CO_2 emissions such as rubber and plastics, water transportation, coke and petroleum and land transportation (though their large contribution to the total emissions), reduce by 1 percent point during the same period.

Apart from the electricity sector, other economic sectors see a considerable change in their emissions (absolute value) during the period 2017- 2040. For example, the CO_2 emissions of land transportation reduce from 15.64 MtCO2 in 2017 to 10.57 $MtCO_2$ by 2040, 32% in the whole period or 1.4% annually; or the emissions of metals sector reduce from 13.72 $MtCO_2$ in 2017 to 8.04 $MtCO_2$ by 2040, 41% in the whole period or 1.7% annually. The emissions of rubber and plastics sector reduce from 23.04 $MtCO_2$ in 2017 to 9.9 $MtCO_2$ by 2040, 57% in the whole period or 2.4% annually. The emissions of water transportation sector reduce from 17.95 $MtCO_2$ in 2017 to 9.33 $MtCO_2$ by 2040, 48% in the whole period or 2% annually. Figure 27 visualizes the changes in CO_2 emissions of 'hotspot' economic sectors.

From consumption perspective, the changes in electricity consumption induce changes in other economic sectors both in percentage points and absolute values, however, it is less obviously shown than that from production perspective. In 2017, the electricity sector accounts for 11.6% of the total CO_2 emissions. By 2040, its share reduces to 5.9%. Apart from the electricity sector, the share of CO_2 emissions of some economic sectors also decrease during the period 2017 and 2040, such as construction sector (reducing 1.1 percent points), health, accommodation and food service, public administration and defend (reducing less than 1 percentage point for each sector). Meanwhile, the shares of CO_2 emissions of some sectors increase such as food and beverage, land transportation, coke and petroleum, transport equipment (increasing less than 1 percent point for each sector). It should be noted that the shares of emissions of these sectors out of the total emissions do not show the absolute increase (or decrease) of the economic sectors' emissions. Instead, these shares relatively present the change in the contribution of these sectors' emissions to the total emission (see also the 'Identification of hotspot sectors' section).

In term of change in the absolute value of the emissions, 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 electricity, decreasing from 34.88 $MtCO_2$ in 2017 to 13.72 $MtCO_2$ by 2040, at about 0.92 $MtCO_2$ annually; food and beverage decreasing from 15 $MtCO_2$ in 2017 to 12.5 $MtCO_2$ by 2040, or 0.1 $MtCO_2$ annually; or healthcare, decreasing from 17.7 $MtCO_2$ in 2017 to 11.43 $MtCO_2$ by 2040, or 0.27 $MtCO_2$ annually. The decrease of CO_2 emissions of economic sectors between 2010 and 2040 can be seen in Figure 27.

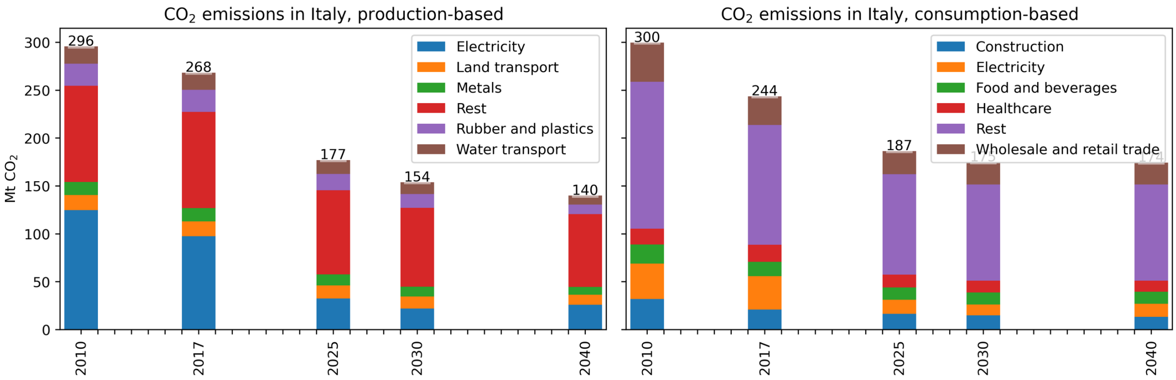


Figure 27. Emissions of other economic sectors

5.2.8. Relations between power consumption and air emissions of economic sectors

There is a correlation between the power consumption and the air emission change through years. Take CO_2 as an example, as mentioned above, most of CO_2 emissions come from the electricity sector, and the wholesale and retail sector. These two sectors contributed up to 27% of the life cycle consumption-based CO_2 emission in 2017. This CO_2 emission value is relevant to the electricity consumption of these two sectors, in which the electricity sector is the top electricity consumer (the own use of electricity in this sector), at 31280 million Euro, and followed by wholesale and retail sector, at 3519 million Euro. By 2040, the CO_2 emission reduction of these two sectors is up to 25.72 million tonne, contributing 64% of the total CO_2 emission reduction in the period 2017-2040.

It should be noted that the emission reduction of the electricity sector reduces by 60% in the period 2017-2040, while that of the wholesale and retail sector only reduces by 17%. It is clear that the pace of emission reduction in the wholesale and retail sector is much slower than that of the electricity sector. Meaning that, the change in emissions of the wholesale and retail sector is not solely dependent on the power consumption. This also occurs in some other sectors, for example, the metal sector consumed about 3227 million Euro of electricity in 2017, being equivalent to about 4.6% of the total output value of the electricity sector. Meanwhile, during the period 2017- 2040, the CO_2 emission reduction of this sector is at 9%, which is lower than the average emission reduction pace of the whole economy, at 14%. In other cases, for example, the hotel and restaurant sector consumes about 3.5% of the electricity sector's output value, or 2458 million Euro. Besides, its emission reduction in the same period reach 29%, or 3.49 million tonne CO_2. From these three cases, it can be concluded that there are some sectors whose CO_2 emissions are largely dependent on the electricity sector, for example the hotel and restaurant sector, while some other sectors, for examples the wholesale and retail, and metals sectors, the correlation between them and the electricity sector are quite loose. Instead, there are other factors that impact their emission reductions (or increase) such as the increase/ decrease in final demand, technological improvements and sectorial efficiency. The relations between power consumptions and emissions of economic sectors are visualized in Figure 28.

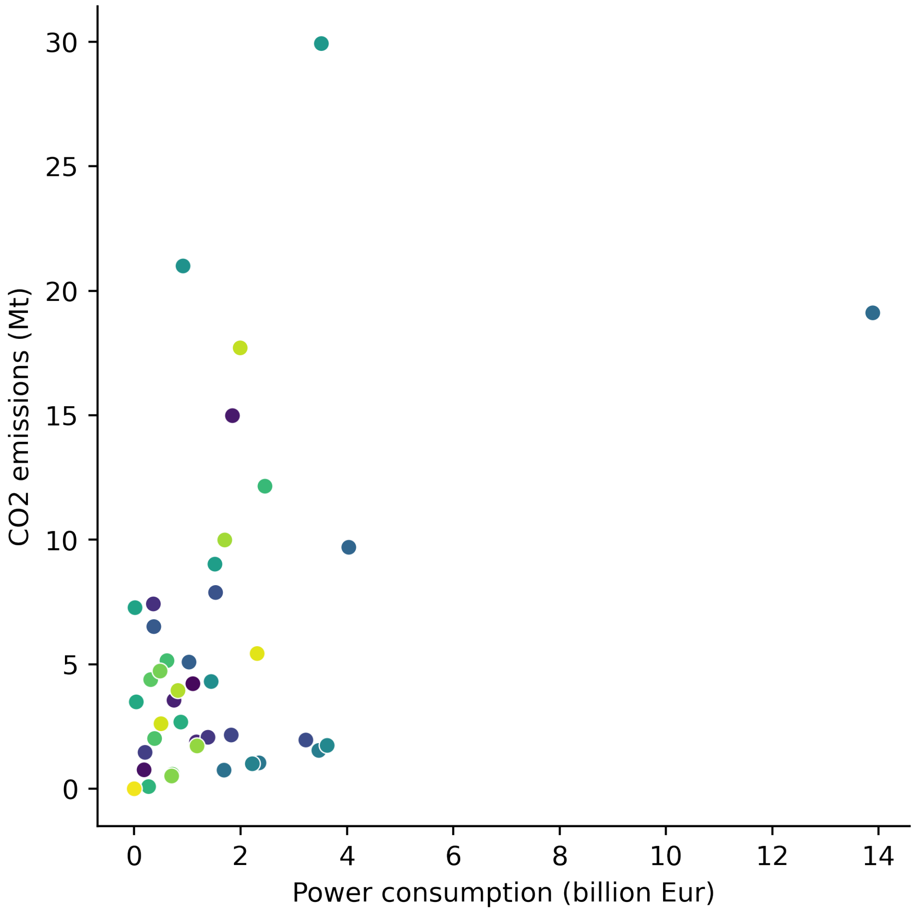


Figure 28. Relations between power consumptions and emissions in 2017

5.2.9. Emissions embodied in import and export

There is a large difference between the emissions of import and export in all air emission categories, presented in Table 28. The largest difference occurs in CO emission, in which CO emission from import equals five times that of export. The smallest difference occurs in NOx, at 19%. It should be noted that the emissions of import are higher than those of export in all air emission categories, indicating that the Italy's import value is larger than its export value, or emission intensities of imported products are larger than those of exported products.

Table 28. Air emissions embodied in import, export and trade in 2017

Air emissions	**Unit**	**Import**	**Import excluding trade**	**Export**	**Trade between Italy and Rest of the World**	**Absolute difference**	**Absolute difference (excluding trade)**
CO_2	Mt	128.22	71.07	95.77	224.00	32.45	-24.70
N_2O	kt	37.54	20.81	19.43	56.97	18.10	1.37
CH_4	kt	1,552.45	860.48	492.32	2,044.77	1,060.13	368.15
NOx	kt	399.63	221.50	322.46	722.09	77.17	-100.96
SOx	kt	472.51	261.90	211.34	683.86	261.17	50.55
NH_3	kt	368.86	204.45	136.46	505.32	232.40	67.99
NMVOC	kt	503.18	278.90	216.70	719.87	286.48	62.20
CO	kt	1,080.89	599.10	204.24	1,285.13	876.64	394.86
PM_{10}	kt	140.47	77.86	45.04	185.51	95.43	32.82
$PM_{2.5}$	kt	95.30	52.82	35.46	130.76	59.84	17.36

For all air emission categories, 44.6% of the emissions embodied in import comes from trade (see Table 28). Meaning that nearly half of the imported products are intermediate products which are used for exporting, after adding some values. If the emissions from trade is excluded from the emissions from import, the difference will be lower. In the cases of CO_2 and NOx, the emissions from import even become lower than those of export.

Table 29 presents the changes in the CO_2 emissions in import and export of Italy from, and to Rest of the World (RoW) over the period from 2010 to 2040. The CO_2 emissions from import sharply decrease from 162.22 $MtCO_2$ to 128 $MtCO_2$ between 2010 and 2017, and gradually and slightly increase to 134.07 $MtCO_2$ by 2040. Meanwhile, the emissions from export, slightly increase from 93.88 $MtCO_2$ to 95.77 $MtCO_2$ between 2010 and 2017, then reduce by half to 42.3 $MtCO_2$ by 2040.

Table 29. CO_2 emissions embodied in import, export and trade

Year	Unit	Import	Export	Trade between Italy and RoW
2010	**$MtCO_2$**	162.22	93.88	256.10
2017	**$MtCO_2$**	128.22	95.77	224.00
2025	**$MtCO_2$**	130.44	63.70	194.15
2030	**$MtCO_2$**	131.64	53.58	185.21
2040	**$MtCO_2$**	134.07	42.30	176.37

Figure 29 presents the contribution of various economic sectors to the CO_2 emissions of import and export. There is a difference between the contribution of economic sectors to import and export. In 2010 and 2017, there is a large contribution of CO_2 emissions from the electricity sector to the emissions embodied in export. During the period 2025-2040, the contribution of the electricity sector sharply decrease. Thanks to the decarbonization of the electricity sector, emissions of domestic production as well as export of this sector reduce accordingly. Six main sectors which contribute most to the emissions of export include electricity, chemical, coke and petroleum, metals, rubber and plastics, and water transportation.

For import, there is a big difference between the emissions of trade, and other economic sectors. Specifically, the CO_2 emissions from trade account for half of the emissions embodied in import. These emissions originate from imported products which are then be exported. This is the same emissions presented in trade (as an economic sector) in consumption-based accounting. Five main sectors which contribute most to the emissions of import include electricity, food and beverages, healthcare, transport equipment and wholesale and retail trade.

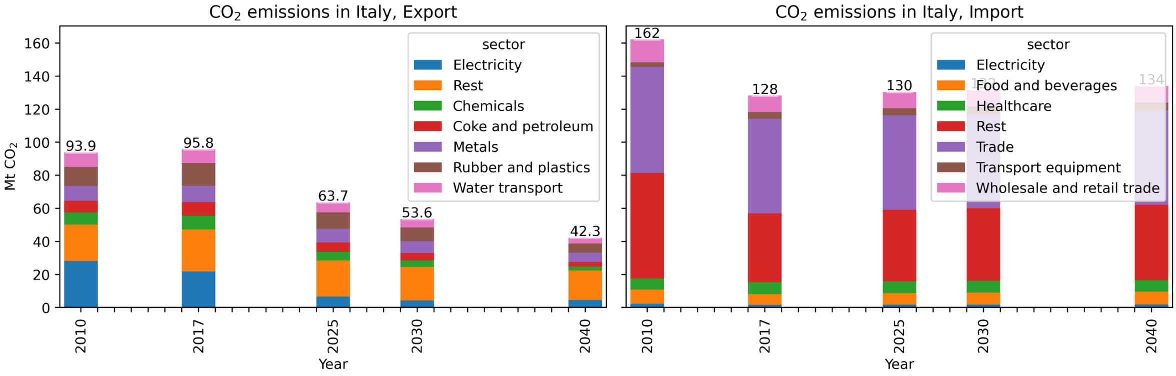


Figure 29. Contributions of economic sectors to emissions embodied in imports and exports

5.2.10.Foreign or domestic dependence in ‘hotpot’ sectors

The emissions from import account for a significant share of the national CBA emissions in most of air emission categories. Specifically, CO_2 emissions embodied in import hold up to 43.9 % of consumption-based emissions. This indicates the outsource of the Italian air emissions, as well as its emission’s 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 Figure 30. Some economic sectors with large shares of air emissions embodied in import compared to those of consumption includes trade, pharmaceutical, computer and electronics, textile and leather, information and communication, transport equipment and etc. For example, 63% of the CO_2 emission in 2017 of the transport equipment sector originates from imported products.

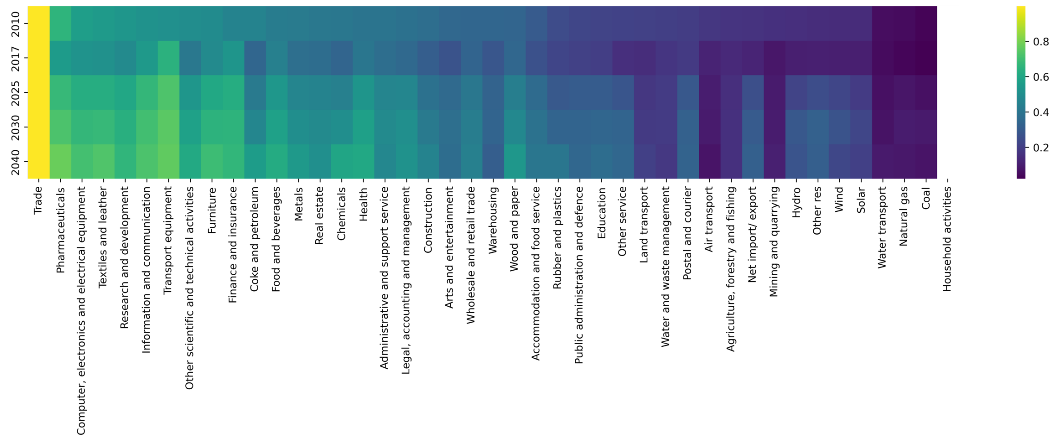


Figure 30. Share of CO_2 emission embodied in import out of consumption by years

During the period of 2017- 2040, 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 the electricity, information and communication, and finance and insurance sectors, at around 11-12 percentage 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 holding the large shares out of the total CBA CO_2 emission includes: wholesale and retail, healthcare, food and beverage, electricity and construction (refer back to identification of hotspot sectors). In 2017, the wholesale and retail sector contributes 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 emission, effort should be focused on these five sectors.

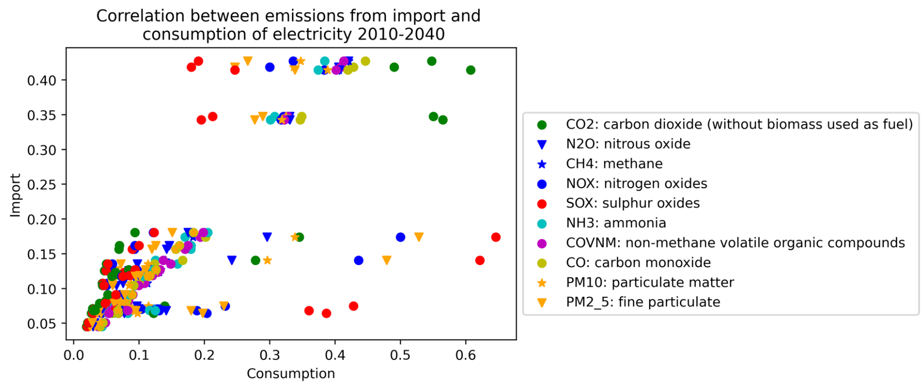
The different contributions of domestic and import emissions to the total emissions suggest that Italy should have proper strategies to reduce its emissions in term of geographical effort. For example, the CO_2 emissions of Italian trade partners for food and beverage, construction, health, wholesale and retail sectors should be taken into account, because the emissions of these sectors largely depend on import (see Figure 30) with the large shares of CO_2 emission originating from import. 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, the equal effort should be shared between local manufacturers and trade partners in renewable power technologies such as power by solar, wind and other renewables.

5.2.11.Italian electricity sector' dependency on foreign resources

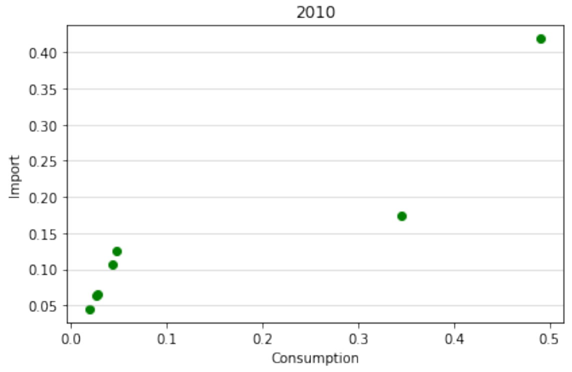
During the period 2017 and 2040, two fossil fuel based technologies (natural gas and coal) are obviously responsible for most of the emissions of the electricity sector, and most of the emissions of these technologies are foreign sourced. However, their contributions gradually reduce in the same period. Figure 31 below indicates the change in contributions of 10 air emissions of different power generation technologies into the total emissions of electricity sector, in relations to the contributions of their import into the specific technologies' emissions during 2017- 2040.

The subplots explain the CO_2 emissions of import and consumption of different electricity technologies out of emissions of the electricity sector in different years. 'Hotspot foreign resource' are technologies whose contributions to the whole electricity sector's CO_2 CBA emission are larger than 50%, and whose contributions to the whole sector's CO_2 import emission are larger than 30%. These electricity technologies have relatively high CO_2 emissions compared to the remaining electricity technologies. Besides their dependencies on import are relatively high compared to the remaining electricity technologies. In this case, electricity by natural gas is identified to be a 'hotspot foreign resources. Its dependency on import increases between 2017-2025, slightly reduces by 2030, and keeps constant until 2040.

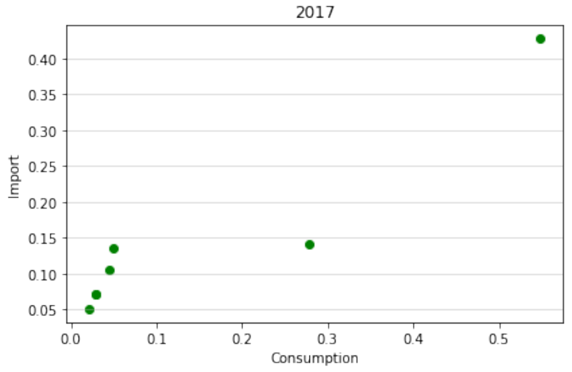
The 'foreign resource' and 'domestic resource' are technologies whose contributions to the whole electricity sector's CO_2 CBA emission are between 20% and 50%. The difference between 'foreign resource' and 'domestic resource' is that contributions of 'foreign resource' technologies to the sector's import emission are larger than 20% while those of 'domestic resources' are smaller than 20%.



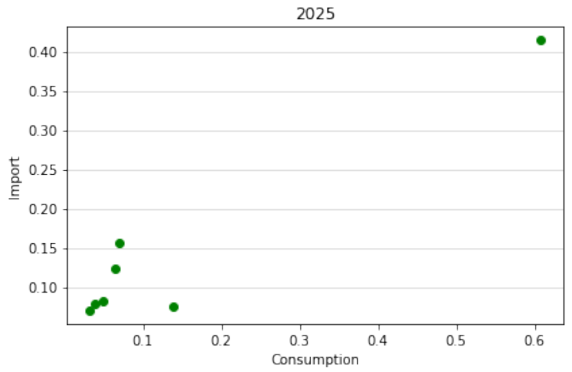
`domestic resources: 2010 CO2 emissions ('IT', 'coal') 0.06`
`foreign resources: 2010 CO2 emissions ('IT', 'natural gas') 0.02`



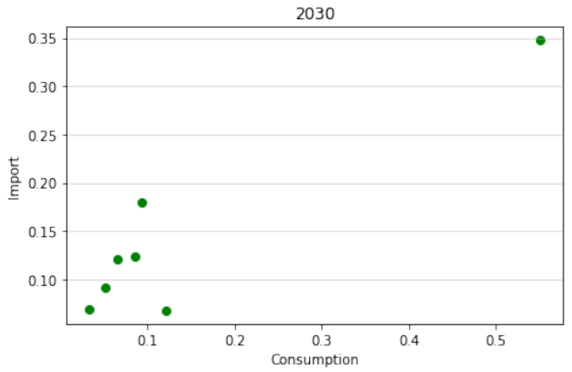
`domestic resources: 2017 CO2 emissions ('IT', 'coal') 0.03`
`hot-spot foreign resource: 2017 CO2 emissions ('IT', 'natural gas') 0.23`



`hot-spot foreign resource: 2025 CO2 emissions ('IT', 'natural gas') 0.25`



`hot-spot foreign resource: 2030 CO2 emissions ('IT', 'natural gas') 0.19`



`hot-spot foreign resource: 2040 CO2 emissions ('IT', 'natural gas') 0.19`

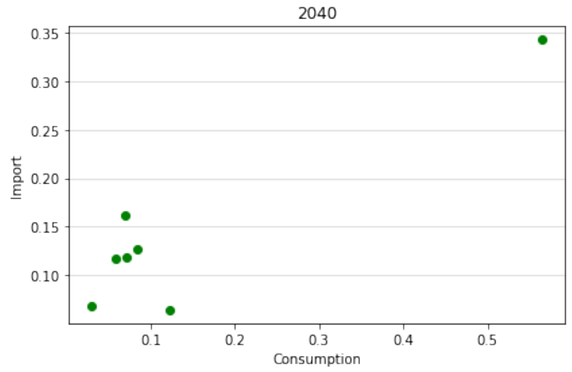


Figure 31. Emissions electricity sector by years and contribution of foreign originated emissions

5.3. Sensitivity analysis

A sensitivity analysis is conducted to verify the role of aggregation in obtained results. Two other models were constructed including 2-regions, 46-52-sectors model and 8-regions, 32-45-sectors model. In the 2-regions, 46-52-sectors model, the number of regions is the same with reference model, but the number of sectors is more detailed, starting with 46 sectors before the hybridization and 52 sectors after the hybridization (46 sectors – 1 electricity sector + 7 electricity generation technologies). In the 8-regions, 32-45-sectors model, the number of regions increases, including Italy, its important electricity trade partners and RoW. The number of sectors is 32 sectors before the hybridization and 45 sectors after the hybridization (32 sectors – 1 electricity sector + 14 electricity generation technologies). The number of regions and sectors of these models are presented in Appendix K.

5.3.1. Global emissions

For the global emissions, there is no difference in the obtained results of the reference year (2017) calculated by different models, and a negligible difference for those of the future years (refer to Table 30). This is because the calculation is conducted based on the same air emission matrices (F matrices) for the reference year. For the future years, the F matrices of Italy are forecasted with different improvement factors for each economic sectors, which causes a corresponding change in the emissions of Italy. The emissions of RoW and other countries are fixed for future scenarios. As the Italian emissions are relatively small compared to the global emissions, any change in Italian emissions in future years causes an insignificant change in the global emissions. This explains for the negligible difference among results of the future years obtained by three models

Table 30. Global emissions calculated with different aggregation rules

Global air emissions	Unit	2017 - 2 regions, 36-42 sectors	2040 - 2 regions, 36-42 sectors	2040 - 2-regions, 46-52-sectors	2040 - 8-regions, 32-45-sectors
CO_2	Gt	34.32	34.20	34.23	34.23
N_2O	Mt	8.83	8.82	8.82	8.82
CH_4	Mt	361.26	360.87	361.03	361.03
NOx	Mt	102.52	102.08	102.08	102.08

SOx	Mt	110.39	110.22	110.01	110.01
NH_3	Mt	83.83	83.77	83.73	83.73
NMVOC	Mt	153.39	153.34	153.44	153.44
CO	Mt	426.99	426.77	426.95	426.95
PM_{10}	Mt	47.40	47.35	47.36	47.36
$PM_{2.5}$	Mt	36.44	36.39	36.40	36.40

5.3.2. *Italy emissions*

The role of regional and sectorial aggregation is clearly shown at the national scale, especially considering the consumption-based perspective. In 2017, the PBA emissions are the same for the models of 2-regions, 36-42-sectors and 2-regions 46-52-sectors, while they are slightly lower in the models of 8-regions, 32-45-sectors (for CO_2, NOx and SOx emissions) (see Table 31). The similarity in the PBA emissions among three models as the modelling is started with the same NAMEA-Air database (the original F matrices). For the hybridization, though ecoinvent database is used for the electricity generation technologies, the difference in the number of electricity generation technologies cause the difference in the PBA results. With the more detail electricity technologies (14 compared to 7 electricity generation technologies), the PBA results obtained with the 8-regions, 32-45-sectors model are lower than those obtained with the 2-regions, 36-42-sectors and 2-regions, 46-52-sectors models. From the consumption perspective, the more detail the models are, the higher the obtained results are (see Table 31). Comparing the two models of 2-regions, there is a small difference in the CBA emissions which are clearly shown in CO_2 and CH_4, and insignificant in other air emissions. The differences in CBA emissions of 2-regions and 8-regions models are quite large, around 30% for most of the air emissions, and up to 50% for CO_2 emission. Notably, the NMVOC emission of 8-regions model is lower than those of 2-regions model. These differences can be explained by differences in the emission coefficients of each economic sectors of Italy as well as of other countries (caused by the aggregation rules).

The difference in the Italian air emission results obtained by three models are more obvious in future years (compared with those of the reference year), for example in 2040, as shown in Table 32. These differences are caused by the combined effect of the forecasted emissions as well as the emission coefficients of the different economic sectors of Italy and other countries.

Table 31 and Table 32 present the Italian emissions in 2017 and in 2040 calculated with different aggregation rules.

Table 31. Italian emissions in 2017 calculated with different aggregation rules

Italian air emissions	Unit	PBA			CBA		
		2-regions, 36-42-sectors	2-regions, 46-52-sectors	8-regions, 32-45-sectors	2-regions, 36-42-sectors	2-regions, 46-52-sectors	8-regions, 32-45-sectors
CO_2	Mt	376.71	376.71	364.52	409.16	410.36	478.31

N_2O	Mt	0.06	0.06	0.06	0.08	0.08	0.11
CH_4	Mt	1.57	1.57	1.57	2.63	2.61	4.07
NOx	Mt	1.03	1.03	1.02	1.11	1.11	1.46
SOx	Mt	0.54	0.54	0.52	0.80	0.80	1.11
NH_3	Mt	0.37	0.37	0.37	0.61	0.60	0.85
NMVOC	Mt	0.92	0.92	0.92	1.20	1.20	1.07
CO	Mt	2.28	2.28	2.28	3.16	3.16	4.26
PM_{10}	Mt	0.23	0.23	0.23	0.33	0.33	0.43
$PM_{2.5}$	Mt	0.20	0.20	0.20	0.26	0.26	0.34

Table 32. Italian emissions in 2040 calculated with different aggregation rules

Italian air emissions	Unit	PBA			CBA		
		2-regions, 36-42-sectors	2-regions, 46-52-sectors	8-regions, 32-45-sectors	2-regions, 36-42-sectors	2-regions, 46-52-sectors	8-regions, 32-45-sectors
CO_2	Mt	248.26	274.95	261.30	340.03	386.30	425.37
N_2O	kt	47.61	49.20	47.77	75.49	76.45	99.66
CH_4	Mt	1.18	1.34	1.18	2.51	2.62	3.99
NOx	Mt	0.58	0.59	0.58	0.88	0.88	1.20
SOx	Mt	0.36	0.16	0.35	0.72	0.58	1.07
NH_3	kt	315.29	268.46	315.07	611.34	574.26	848.81
NMVOC	Mt	0.86	0.97	0.86	1.23	2.60	1.08
CO	Mt	2.06	2.24	2.06	3.11	3.31	4.21
PM_{10}	kt	178.42	184.08	178.22	306.93	316.09	411.74
$PM_{2.5}$	kt	151.28	157.48	150.65	239.62	243.72	312.17

5.3.3. Hotspot identification

From the production perspective, there is small difference in the hotpot sectors being identified by three models, for example, the CO_2 emission hotspot sectors as presented in Figure 32. The difference lies in the third hotspot sector, e.g. rubber and plastics in 2-regions 36-42-sectors and 8-regions 32-45-sectors models, compared to other non-metallic minerals in 2-regions 46-52-sectors model. Moreover, the difference lies in the 7th and 8th hotspot sectors, in which the position of metals and chemicals (and pharmaceuticals) sectors are in interchanged. These differences occur due to the aggregation of several economic sectors into one in 2-regions 36-42-sectors and 8-regions 32-45-sectors models. In contrast, in 2-regions 46-52-sectors model, the rubber, plastics and other non-metallic minerals sector are two separate sectors. As the emissions from the other non-metallic minerals are much larger than those of rubber and plastics, the other non-metallic minerals ranks third in the contribution to PBA CO_2 emission in 2-regions 46-52-sectors model.

This is also the same explanation of the ranking of the metals and chemicals (and pharmaceuticals) sectors, in which in 2-regions 36-42-sectors, the chemicals and pharmaceuticals sectors are separated, while they are grouped into one sector in 2-regions 46-52-sectors and 8-regions 32-45-sectors models. Moreover, the metals sector is separated into two sectors of metals and metallic products in 2-regions 46-52-sectors model; and modelled as one sector in the two remaining models.

Similarly, from consumption-based perspective, the ranking of hotspot sectors slightly changes due to the aggregation rules (presented in Figure 33). In the two models of 2-regions 36-42-sectors and 8-regions 32-45-sectors, the wholesale and retail trade is modelled as one economic sector, as a result, it ranks first in the contribution to the CBA CO_2 emissions of Italy. In the model of 2-regions 46-53-sectors, the wholesale and retail trade is separated into two sectors of (1) wholesale trade and (2) retail trade. In this case, retail trade ranks the fifth and wholesale trade ranks the seventh in the contribution to the Italian CBA CO_2 emissions.

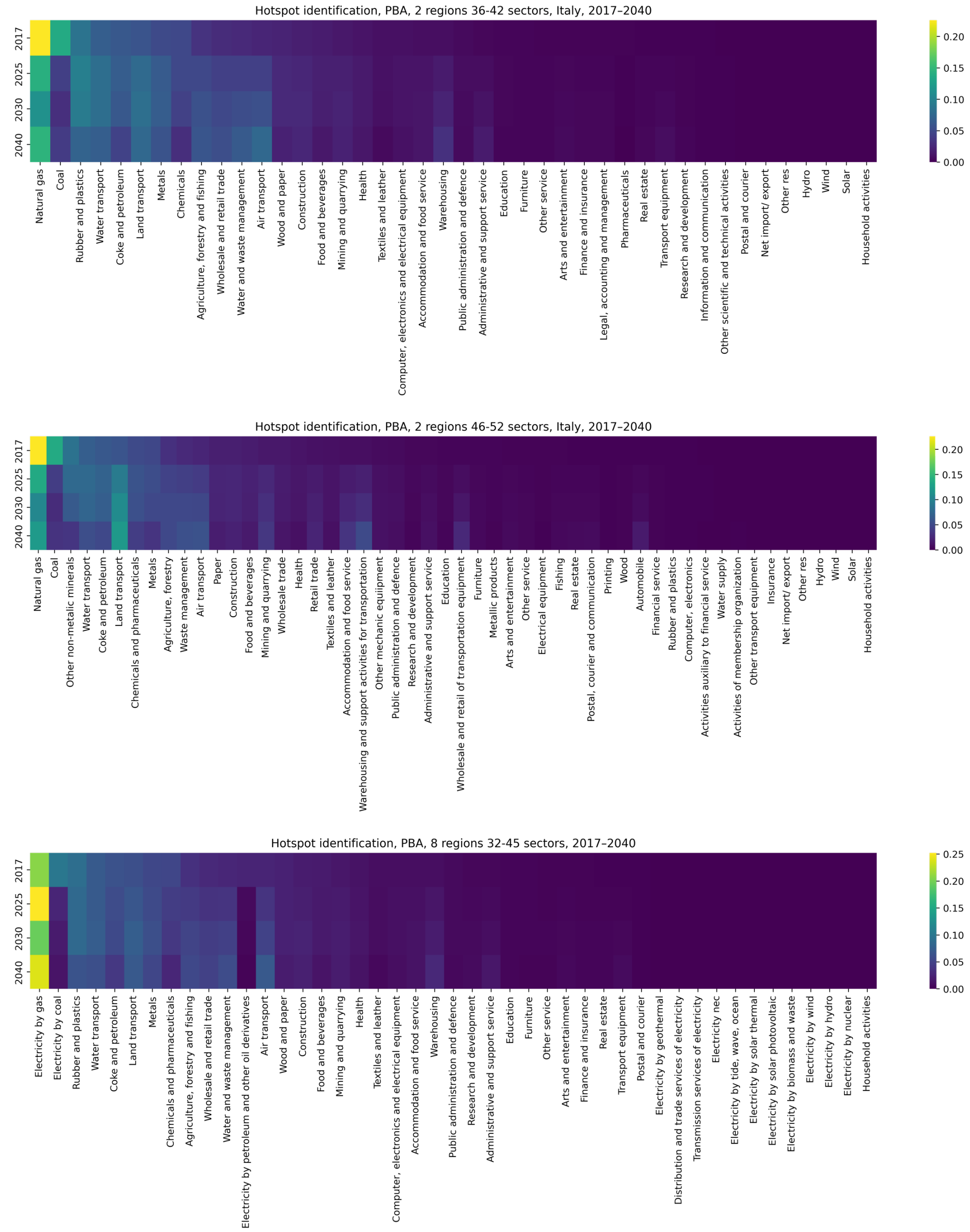
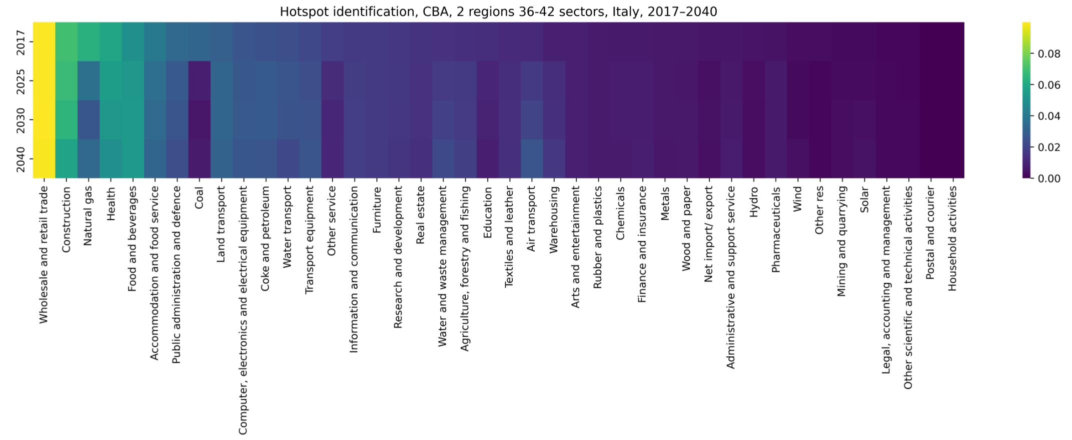
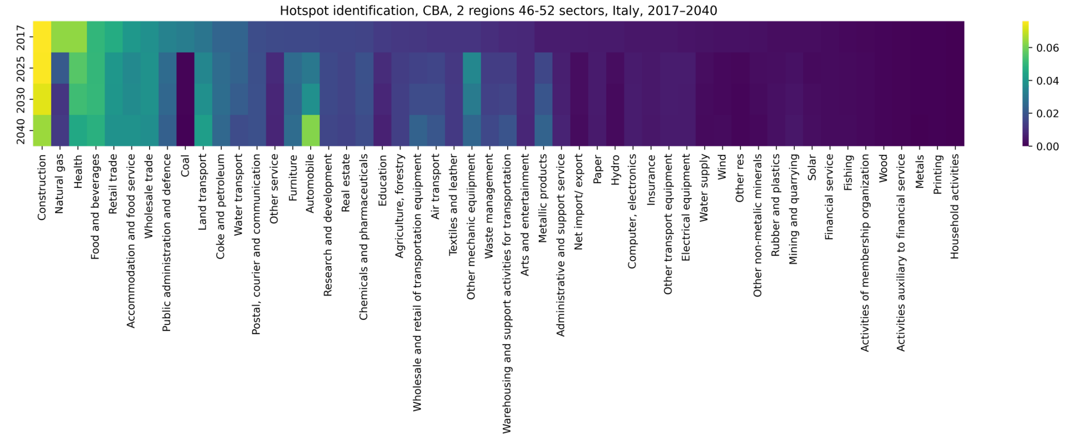


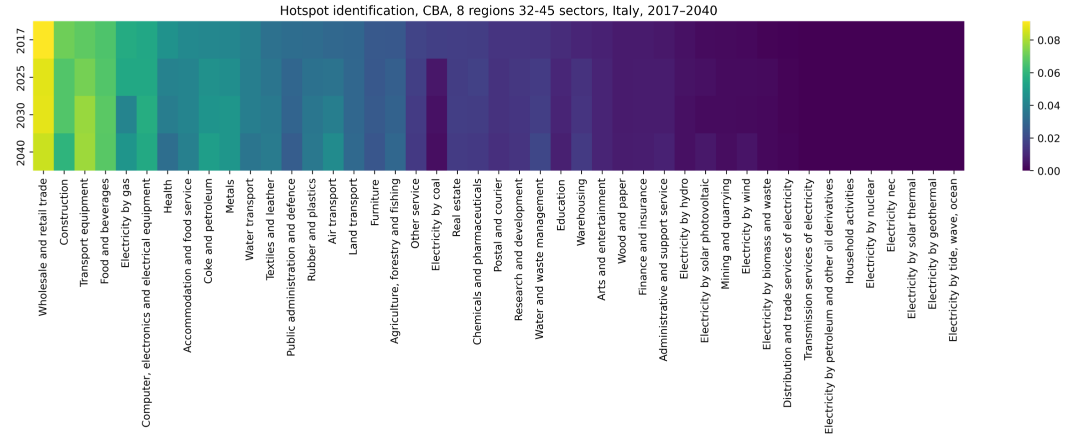
Figure 32. PBA hotspot sectors identified by three models



Hotspot identification, CBA, 2 regions 36-42 sectors, Italy, 2017–2040



Hotspot identification, CBA, 2 regions 46-52 sectors, Italy, 2017–2040



Hotspot identification, CBA, 8 regions 32-45 sectors, Italy, 2017–2040

Figure 33. CBA hotspot sectors identified by three models

5.3.4. Emissions from electricity sector

From the production-based perspective, there is no difference in the air emissions of the Italian electricity sector in 2017 obtained by the two models of 2-regions 36-42-sectors and 2-regions 46-52-sectors. These two models using the same aggregation for the electricity sector (separating into seven electricity generation technologies after the hybridization), as a result, the PBA air emissions of the Italian electricity sectors of the two models are the same. In the model of 8-regions 32-45-sectors, the number of electricity generation technologies is larger (than those in the other two models); therefore, the calculation is more accurate and specific to 14 electricity generation technologies. In this case, the emissions of the Italian electricity sector are lower in all categories (refer to Figure 34).

In future scenarios, the results obtained by the two models of 2-regions 36-42-sectors and 2-regions 46-52-sectors are the same. However, the results obtained by the model of 8-regions 32-45-sectors are higher in CO_2, N_2O, CH_4, NOx and CO emissions; while being lower for SOx, NH_3, NMVOC, PM_{10} and $PM_{2.5}$ emissions, compared to those of the other two models in the corresponding future years (refer to Figure 34).

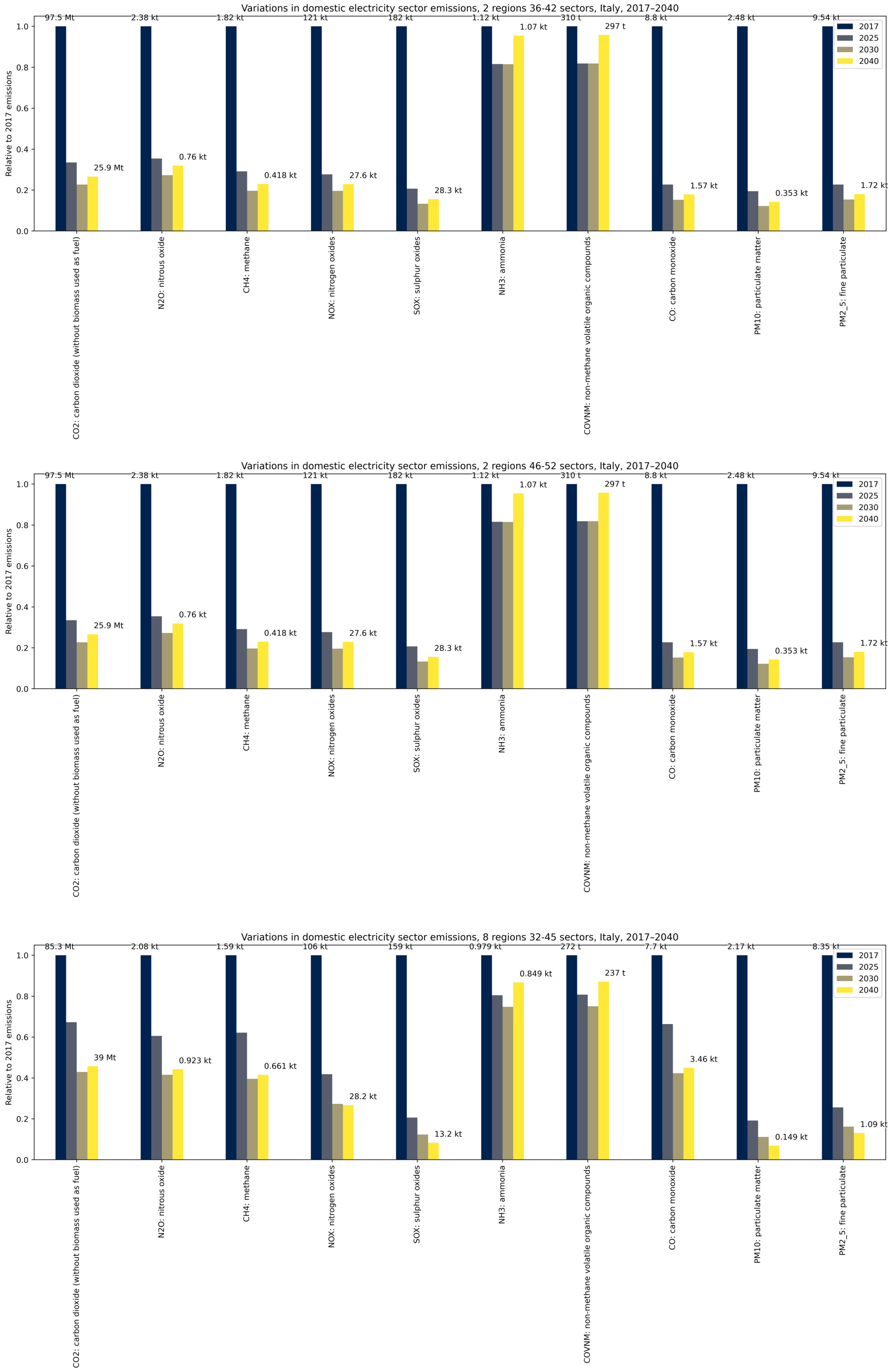


Figure 34. Air emissions of electricity sector, calculated by three models

Regarding the specific electricity generation technologies, there is no difference in the results obtained by the two models of 2-regions 36-42-sectors and 2-regions 46-52-sectors. However, the results obtained by the model of 8-regions 32-45-sectors are more specific, thanks to the increased number of electricity generation technologies in the 8-regions 32-45-sectors model (refer to Figure 35). Notably, in the model of 8-regions 32-45-sectors, the PBA CO_2 emissions from the electricity sector is shared by three technologies of electricity by coal, electricity by gas and electricity by petroleum and other oil derivatives. By 2025, there is a drop in CO_2 emissions from electricity by coal and electricity by petroleum and other oil derivatives. However, the PBA CO_2 emission from electricity by gas keeps constant, and only reduce by 2030 and 2040.

The CBA CO_2 emission of the electricity sector shares the same pattern with the PBA emission, in which there is no difference in the results obtained by the two models of 2-regions 36-42-sectors and 2-regions 46-52-sectors. The CBA CO_2 emission of the Italian electricity sector in 2017 of the 8-regions 32-45-sectors model is lower than that of the other two models; however, in future years, they are higher than those of the other two models (refer to Figure 35).

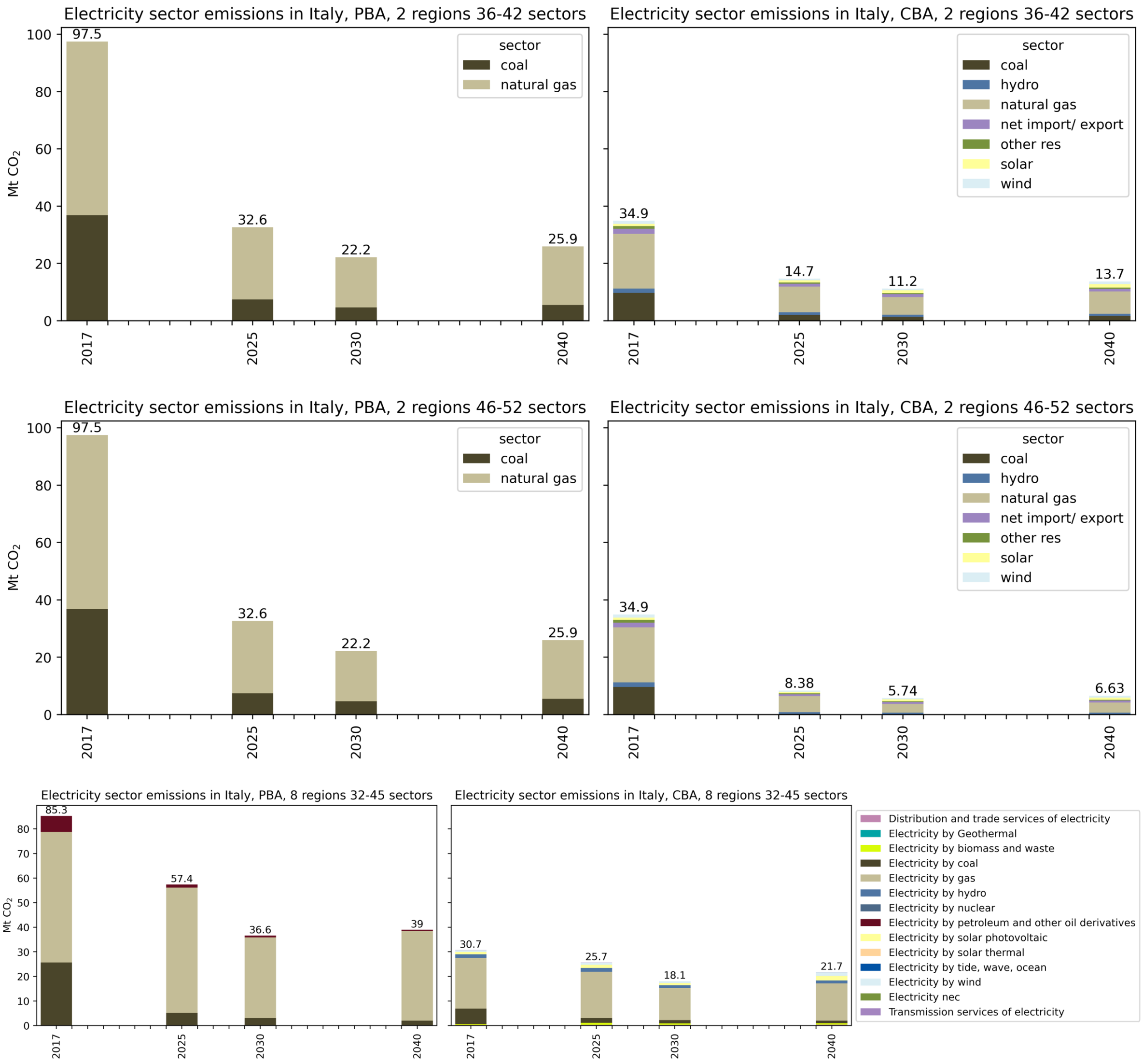


Figure 35. CO_2 emission of electricity sector calculated by three models

5.3.5. Emissions from other economic sectors

The Figure 36 presents the Italian CO_2 emission and the contributions of different economic sectors to the national emission. Comparing the two models of 2-regions 36-42-sectors and 2-regions 46-52-sectors, the CO_2 emission pattern is quite similar, in which the national PBA CO_2 emission is higher than CBA CO_2 emission in 2017. In future years, the national CO_2 emission reduces in both perspectives. However, the rate of CO_2 emission reduction is slower in CBA compared to PBA, which causes a higher CBA CO_2 emission in future years. The difference in national CO_2 emission of the two models comes from the difference in each economic sector's emission (refer to the section 'hotspot identification').

Comparing the two models of 2-regions with the model of 8-regions, the PBA emissions of the three models are quite similar. Meanwhile, there is a significant difference in CBA emissions. The CBA CO_2 emission of the 8-regions model is considerably higher than that of the two models of 2-regions. In the two models of 2-regions, trade activities (import and export) are treated as a separate sector and being excluded in this reported results, meanwhile in the model of 8 regions, trade activities are shared among different economic sectors. This causes a higher national CBA CO_2 emission as well as higher CBA CO_2 emissions in all economic sectors in the 8-regions model.

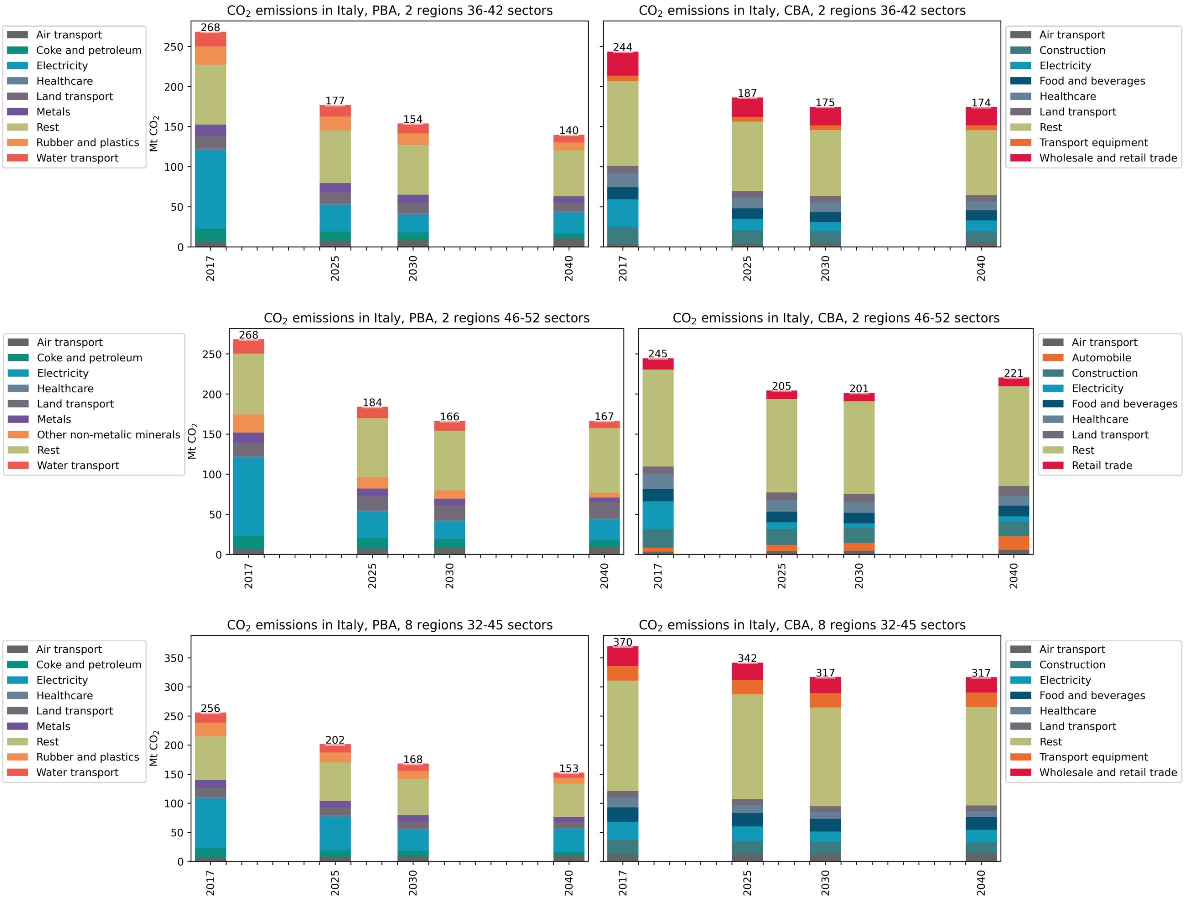


Figure 36. CO$_2$ emission of other economic sectors calculated by three models

5.3.6. Emissions from import and export

Figure 37 presents the Italian import and export CO_2 emission and the contributions of different economic sectors to the emissions embodied in trade activities. Comparing the two models of 2-regions 36-42-sectors and 2-regions 46-52-sectors, both the CO_2 emissions embodied in import and export are quite similar. The CO_2 emission embodied in import is at 94~95.8 $MtCO_2$ and reduces to 53.5 and 43.3 by 2040 in 2-regions 46-52-sectors model and 2-regions 36-42-sectors model, respectively. The CO_2 emission embodied in export in both models decreases from 128 $MtCO_2$ in 2017 to 134 $MtCO_2$ by 2040.

Comparing the two models of 2-regions with the model of 8-regions, the emissions of the Italian export is lower in 8-regions model, but that of import is higher. Specifically, with 8-regions model, the Italian export emits 71.4 $MtCO_2$ in 2017, and reduces by two thirds, to 29.9 $MtCO_2$ by 2040. Meanwhile, the Italian import's CO_2 emission slightly increases from 192 to 199 $MtCO_2$ between 2017 and 2040. The significant difference between CO_2 emissions embodied in trade activities obtained by 2-regions models and 8-regions model indicates the important role of regional aggregation to the accuracy of obtained results related to the emissions of trade activities.

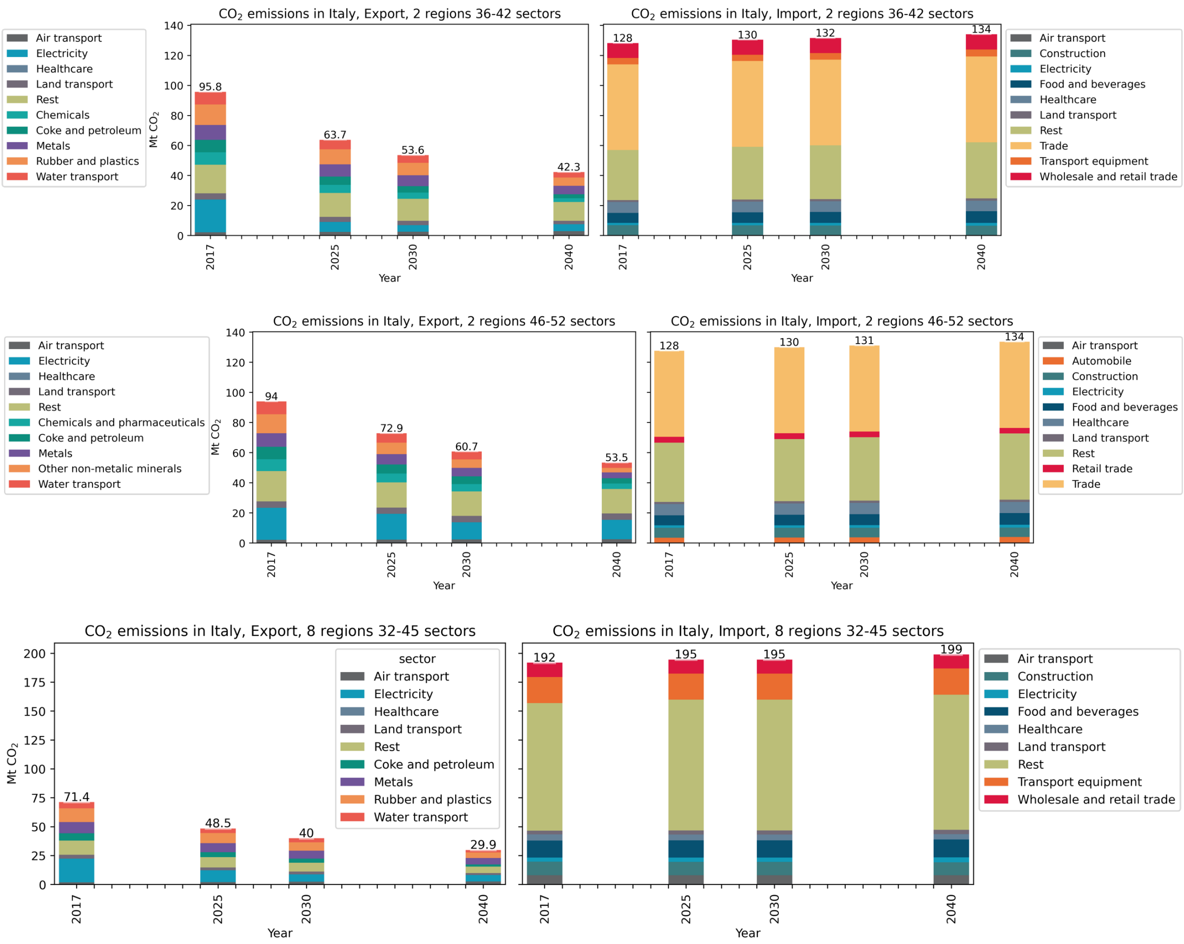


Figure 37. CO$_2$ emission of export and import calculated by three models

5.3.7. Some highlights on sensitivity analysis

- The aggregation of economic sectors has strong impacts on emissions in future years, and moderate impacts on emissions in reference years.
- The aggregation of electricity generation technologies has direct and strong impacts on PBA emissions.
- The aggregation of regions has strong impacts on emissions of import and export.
- The aggregation of regions and economic sectors impacts the CBA emissions more than the PBA emissions, and the emissions from import more than the emissions from export.

5.4. Discussion on methodological framework

Similar to IOA, H-MRIO is a static model. Though some 'dynamic' factors has been integrated into the model by adding power development scenarios, and some changes in final demand. There are some limitations belonging to the 'static' characteristic 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 scenario, 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 difference among power generation technologies.

Moreover, the hybridization is the time-consuming process. For the development of MRIO matrix, Istat and EXIOBASE data need to be matched. The economic sectors of these two databases are classified differently; and there is also a variation in the level of sectoral aggregation. For hybridization of environmental burdens, the ecoinvent and NAMEA data need to be matched. Again the different level of detailness between two data sets requires time for matching them, and in some cases it is impossible to match the two data sets. Gas supply sector accounts for a small percentage of economic values of the electricity, gas and steam sector in the IOT; however, gas supply technologies' CH_4 emission intensity are higher than those of power supply technologies. The omission of gas supply sector during the hybridization of matrix A, and consequently hybridization of environmental burden will neglect the CH_4 emission from gas supply technologies, and hinder the risk of causing CH_4 emission gap in actual and quantified (by this study) emission. It is suggested that in future studies, the level of aggregation should be more specified to reflect the diverse of technologies in electricity, gas and steam sector.

The integration of future power development scenario utilize the similar intermediate flow matrix (for other economic sectors excluding electricity sector). Though the future intermediate flow matrix may be similar to the current one in 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 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 in the data availability for power development scenarios. Considering that recent EU policies such as Fit for 55 are internalized into national policy, in which the new Emission Trading System that will be applied to private transportation and buildings, there will be 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 system and hydrogen; as well as emission reduction options related to social behaviour change. In that context, a comprehensive (and updated) energy development scenario should be developed, and should extend from electricity sector to the economic-wide sectors.

CHAPTER 6. CONCLUSION

The thesis quantified and evaluated the consequential life cycle air emissions and impacts of Italian electricity sector and national emissions. The decarbonization of the Italian electricity sector has positive impacts on the GHG and other air emissions of the sector itself as well as the national economy. By 2040, the Italian electricity sector will be developed towards decreasing electricity by coal, and replacing by electricity by solar and electricity by wind.

The total GHG emissions to meet global final demand in 2017 calculated in the study is at 47.69 $GtCO_2e$. Another calculation for GHGs from combustion activities only 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 accounts up to 70% of the total GHG emissions. Moreover, these obtained results on global emissions are very close to the available results calculated with other models.

The national GHG emissions of Italy in 2017 were 441 and 510 $MtCO_2e$, by production and consumption perspectives, respectively. Between 2010 and 2040, the Italian emissions tend to reduce in all air emission categories, considering the production emissions. Meanwhile, from the consumption perspective, the general trend is the decrease in most air emission categories, except for NH3 and NMVOC during the same period.

A decomposition analysis has been conducted in order to look into details of the sources of the change in the air emission. With the change in final demand and electricity sector composition of Italy, consumption-based GHG emissions appear to decrease in the period 2010-2040. 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 $MtCO_2$. While the change in production structure, including 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.

Due to the change in power supply technologies and power consumption, the future air emissions dramatically reduce in electricity sector. Most of the emissions of the domestic electricity production come from fossil fuel based electricity, e.g. electricity by coal and natural gas. The reduction in electricity from fossil fuels such as coal and natural gas help to reduce the emissions of the domestic electricity production nearly four times from 97.5 $MtCO_2$ in 2017 to 25.9 $MtCO_2$ by 2040. Besides, the CO_2 emission of final consumption of electricity is 34.9 $MtCO_2$ in 2017, which reduces by more than half, at 13.7 $MtCO_2$ by 2040. The CO_2 emission of final electricity consumption is divided among technologies by their production structure, including emissions from low-carbon technologies such as solar and wind power technologies.

The changes in energy transition scenarios induce changes in other economic sectors over the supply chain of low carbon electricity technologies. The CO_2 emission decrease is clearly presented in economic sectors such as land transportation, decreasing from 15.64 $MtCO_2$ in 2017 to 10.57 $MtCO_2$ by 2040; or metals, decreasing from 13.72 $MtCO_2$ to 8.04 $MtCO_2$; or rubber and plastics, decreasing from 23.04 $MtCO_2$ to 9.9 $MtCO_2$; or water transportation, decreasing from 17.95 $MtCO_2$ to 9.33 $MtCO_2$.

The obtained results relevant to trade activities point out the important contribution of imports in the national air emissions. Trade, pharmaceutical, computer and electronics, textile and leather, information and communication, and transport equipment, are particularly high importers of embodied carbon. Specifically, 63% of CO_2 emission in 2017 of transport equipment sector originates from imported products. This suggests the need of international measures to further reduce emissions embodied in imported products.

The sensitivity analysis highlights the role of sectorial and regional aggregation in emission quantification. The numbers of economic sectors and electricity generation technologies have strong impacts on the national emission and emissions of individual sectors. Meanwhile, the number of regions have strong impacts on the emission embodied in import, export and trade activities. In any cases, the increasing number of sectors and regions improves the transparency of the model. However, it will take more time for collecting the specific sectoral and regional data.

APPENDIX

Appendix K. Aggregation of regions and sectors in three models

Codes	2 Regions	8 Regions
IT	Italy	Italy
RoW	Rest of the World	Rest of the World
AT		Austria
CH		Switzerland
FR		France
GR		Germany
SI		Slovenia
MT		Malta

Codes	36 Sectors	42 Sectors	Codes	46 Sectors	52 Sectors	Codes	32 Sectors	45 Sectors
A.01	Agriculture, forestry and fishing	Agriculture, forestry and fishing	A.01	Agriculture, forestry	Agriculture, forestry	A.01	Agriculture, forestry and fishing	Agriculture, forestry and fishing
			A.02	Fishing	Fishing			
B.02	Mining and quarrying	Mining and quarrying	B.03	Mining and quarrying	Mining and quarrying	B.02	Mining and quarrying	Mining and quarrying
C.03	Food and beverages	Food and beverages	C.04	Food and beverages	Food and beverages	C.03	Food and beverages	Food and beverages
C.04	Textiles and leather	Textiles and leather	C.05	Textiles and leather	Textiles and leather	C.04	Textiles and leather	Textiles and leather
C.05	Wood and paper	Wood and paper	C.06	Wood	Wood	C.05	Wood and paper	Wood and paper
			C.07	Paper	Paper			

Codes	36 Sectors	42 Sectors	Codes	46 Sectors	52 Sectors	Codes	32 Sectors	45 Sectors
			C.08	Printing	Printing			
C.06	Coke and petroleum	Coke and petroleum	C.09	Coke and petroleum	Coke and petroleum	C.06	Coke and petroleum	Coke and petroleum
C.07	Chemicals	Chemicals	C.10	Chemicals and pharmaceuticals	Chemicals and pharmaceuticals	C.07	Chemicals and pharmaceuticals	Chemicals and pharmaceuticals
C.08	Pharmaceuticals	Pharmaceuticals						
C.09	Rubber and plastics	Rubber and plastics	C.11	Rubber and plastics	Rubber and plastics	C.09	Rubber and plastics	Rubber and plastics
			C.12	Other non-metalic minerals	Other non-metalic minerals			
C.10	Metals	Metals	C.13	Metals	Metals	C.10	Metals	Metals
			C.14	Metallic products	Metallic products			
C.11	Computer, electronics and electrical equipment	Computer, electronics and electrical equipment	C.15	Computer, electronics	Computer, electronics	C.11	Computer, electronics and electrical equipment	Computer, electronics and electrical equipment
			C.16	Electrical equipment	Electrical equipment			
			C.17	Other mechanic equiipment	Other mechanic equiipment			
C.12	Transport equipment	Transport equipment	C.18	Automobile	Automobile	C.12	Transport equipment	Transport equipment
			C.19	Other transport equipment	Other transport equipment			
C.13	Furniture	Furniture	C.20	Furniture	Furniture	C.13	Furniture	Furniture

Codes	**36 Sectors**	**42 Sectors**	**Codes**	**46 Sectors**	**52 Sectors**	**Codes**	**32 Sectors**	**45 Sectors**
D.14	Electricity and gas	Electricity by coal	D.21	Electricity, gas and steam	Electricity by coal	D.14	Electricity and gas	Electricity by coal
		Electricity by gas			Electricity by gas			Electricity by gas
		Electricity by solar photovoltaic			Electricity by solar photovoltaic			Electricity by nuclear
		Electricity by wind			Electricity by wind			Electricity by hydro
		Electricity by hydro			Electricity by hydro			Electricity by wind
		Electricity by other RES			Electricity by other RES			Electricity by petroleum and other oil derivatives
		Electricity net import/ export			Electricity net import/ export			Electricity by biomass and waste
								Electricity by solar photovoltaic
								Electricity by solar thermal
								Electricity by tide, wave, ocean
								Electricity by Geothermal

Codes	36 Sectors	42 Sectors	Codes	46 Sectors	52 Sectors	Codes	32 Sectors	45 Sectors
								Electricity nec
								Transmission services of electricity
								Distribution and trade services of electricity
E.15	Water and waste management	Water and waste management	E.22	Water supply	Water supply	E.15	Water and waste management	Water and waste management
			E.23	Waste management	Waste management			
F.16	Construction	Construction	F.24	Construction	Construction	F.16	Construction	Construction
G.17	Wholesale and retail trade	Wholesale and retail trade	G.25	Wholesale and retail of transportation equipment	Wholesale and retail of transportation equipment	G.17	Wholesale and retail trade	Wholesale and retail trade
			G.26	Wholesale trade	Wholesale trade			
			G.27	Retail trade	Retail trade			
H.18	Land transport	Land transport	H.28	Land transport	Land transport	H.18	Land transport	Land transport
H.19	Water transport	Water transport	H.29	Water transport	Water transport	H.19	Water transport	Water transport
H.20	Air transport	Air transport	H.30	Air transport	Air transport	H.20	Air transport	Air transport
H.21	Warehousing	Warehousing	H.31	Warehousing and support activities for transportation	Warehousing and support activities for transportation	H.21	Warehousing	Warehousing

Codes	**36 Sectors**	**42 Sectors**	**Codes**	**46 Sectors**	**52 Sectors**	**Codes**	**32 Sectors**	**45 Sectors**
H.22	Postal and courier	Postal and courier	H.32	Postal, courier and communication	Postal, courier and communication	H.22	Postal and courier	Postal and courier
I.23	Accommodation and food service	Accommodation and food service	I.33	Accommodation and food service	Accommodation and food service	I.23	Accommodation and food service	Accommodation and food service
J.24	Information and communication	Information and communication						
K.25	Finance and insurance	Finance and insurance	K.34	Financial service	Financial service	K.25	Finance and insurance	Finance and insurance
			K.35	Insurance	Insurance			
			K.36	Activities auxiliary to financial service	Activities auxiliary to financial service			
L.26	Real estate	Real estate	L.37	Real estate	Real estate	L.26	Real estate	Real estate
M.27	Legal, accounting and management	Legal, accounting and management						
M.28	Research and development	Research and development	M.38	Research and development	Research and development	M.28	Research and development	Research and development
M.29	Other scientific and technical activities	Other scientific and technical activities						
N.30	Administrative and support service	Administrative and support service	N.39	Administrative and support service	Administrative and support service	N.30	Administrative and support service	Administrative and support service

Codes	36 Sectors	42 Sectors	Codes	46 Sectors	52 Sectors	Codes	32 Sectors	45 Sectors
O.31	Public administration and defence	Public administration and defence	O.40	Public administration and defence	Public administration and defence	O.31	Public administration and defence	Public administration and defence
P.32	Education	Education	P.41	Education	Education	P.32	Education	Education
Q.33	Health	Health	Q.42	Health	Health	Q.33	Health	Health
R.34	Arts and entertainment	Arts and entertainment	R.43	Arts and entertainment	Arts and entertainment	R.34	Arts and entertainment	Arts and entertainment
S.35	Other service	Other service	S.44	Activities of membership organization	Activities of membership organization	S.35	Other service	Other service
			S.45	Other service	Other service			
T.36	Household activities	Household activities	T.46	Household activities	Household activities	T.36	Household activities	Household activities

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Luu, L.Q.; Longo, S.; Cellura, M.; Sanseverino, R.E.; Cusenza, M.A.; Franzitta, V.A. Conceptual Review on Using Consequential Life Cycle Assessment Methodology for the Energy Sector. Energies 2020, 13, 3076, doi:https://doi.org/10.3390/en13123076.

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