Master's thesis

Marginal Abatement Cost Curves in TIMES-Italy

Energy and Nuclear Engineering
Department of Energy
Politecnico di Torino

Marco Bosco

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Supervised by Prof. Laura Savoldi
Dr. Daniele Lerede
Eng. Gianvito Colucci

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Chiundo dicendo che è stata veramente una bellissima avventura, ricca di emozioni e avvenimenti, ma dopo tutto ciò, giungedo finalmente alla conslusione posso solo dire:
evviva.

Uomini forti, destini forti; uomini deboli, destini deboli; non c'è altra strada.

Abstract

Around three-quarters of greenhouse gases emissions today are produced by the energy sector, which represents indeed a key point of action to tackle the climate change issue. Reducing global carbon dioxide emissions to net-zero by 2050 is consistent with the efforts to limit the long-term increase in average global temperatures to 1.5 °C. This means that a radical transformation of how the way energy is produced, transported and consumed is necessary [1]. The Agenda 2030 and the Paris Agreement on climate change require a transformation shift of our economies and societies towards climate resilient and sustainable development. The European Union aims to achieve carbon-neutrality by 2050 through a socially-fair transformation of its economy.

This research explores decarbonization options and scenarios using an innovative analytical approach that combines energy systems analysis, using the TIMES model, and marginal abatement cost curves.

The goal of this thesis is indeed to understand the role of each technology, within the different sectors of the economy in several, alternative decarbonization scenarios to assist informed decision making. The work should also help to identify possible gaps in the development of some sectors in terms of available low-carbon technologies. For this work, a model-based approach is used to compute marginal abatement cost curves. They are useful tools which illustrate the economics of climate change mitigation and have contributed to decision making in the context of climate policy, although usually adopting an expert-based approach [2].

The model used for this work is TIMES-Italy, therefore a model used to represent the Italian energy system. The TIMES model generator is used for the generation of long-term energy scenarios to conduct energy and environmental analyses. The TIMES model generator combines two different, but complementary, systematic approaches to modelling energy: a technical engineering approach and an economic approach. TIMES is a technology rich, bottom-up model generator, which uses linear-programming to produce a least-cost energy system, optimized according to a number of user constraints, over medium to long-term time horizons [3].

The marginal abatement cost curves are a standard tool used to illustrate the supply-side economics of abatement initiatives aimed at reducing emissions of pollutants. Starting from an estimate of baseline emissions, the costs and potential for additional abatement measures are calculated so as to build a menu of options for abatement. The marginal abatement cost curves are widely used to inform the climate debate on the available potential for greenhouse gases emission reductions and their costs. The success and the interest of these curves lies is due to their ability to summarize, in a single representation, a complex set of information: the type of greenhouse gas emission reduction potentials, the quantity of emissions avoided, the ranking of measures according to their average cost over a given period. They are evaluated here on a national level (Italy) and on a time scale up to 2050 [4].

The results of the analysis show that focusing all efforts for emissions reductions by the end of the examined time scale reflects in a huge cost for reducing emissions. A marginal cost curve is indeed obtained showing the contribution of the different sectors to progressive levels of decarbonization, highlighting the huge role of hard-to-abate sectors (industry and transport).

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1 Introduction

As the global community strives to address the challenges posed by climate change, the reduction of carbon dioxide (CO2) emissions has become a paramount objective.

The Earth is warming and scientists are more and more confident that this is due to the rise in greenhouse gas emissions caused by industrialization and in general by antropic activities. Some of the major effects clearly visible of the increasing of temperatures are the melting of snow and ice and rising sea levels and in general a change of the global climate, whether as increased rainfall and more frequent storms in some parts of the world, or more intense and longer droughts in others. Continued emissions at or above current rates will cause more warming and bigger climate changes in the years ahead. The impact on fresh water access, food production and health is likely to be destructive over time. A recent report by the Intergovernmental Panel on Climate Change (IPCC) points out some serious risks to the global economy and human society if no action is taken [5].

The presence of emissions already present in the atmosphere requires the acknowledgment that some degree of climate change is inevitable. Striking a balance between adapting our economy to accommodate these changes and taking action to prevent further, more severe climate change is crucial. It is important to note that the speed and depth at which we attempt to reduce emissions directly impact the potential short-term costs [4]. However, delaying such action increases the likelihood of incurring even greater long-term costs. The management of these choices requires careful consideration, but there is a growing international scientific consensus in support of urgent action. It is, therefore, essential that the international community steps up its efforts towards meeting the Paris Agreement objectives of:

- holding the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognising that this would significantly reduce the risks and impacts of climate change;
- increasing the ability to adapt to the adverse impacts of climate change and foster climate resilience and low greenhouse gas emissions development, in a manner that does not threaten food production;
- making finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development.

The aim of this thesis is to quantify the potential costs associated with reducing CO2 emissions across different sectors and through the adoption of various technological solutions. By understanding the economic implications of emission reduction efforts, policymakers and stakeholders can make informed decisions to achieve sustainable and cost-effective mitigation strategies. The accumulation of CO2 in the Earth's atmosphere is a leading cause of global warming and climate change [6]. To mitigate the adverse effects of climate change, it is crucial to identify and quantify the costs involved in reducing CO2 emissions within specific sectors and through the implementation of technological advancements. This work seeks to shed light on these costs and provide insights into effective climate change mitigation strategies [7].

In 2022, global carbon dioxide (CO2) emissions resulting from energy combustion and industrial processes increased by 0.9%, totaling 321 million metric tons and reaching a record high of 36.8 gigatons [5].

This rise in emissions follows two years marked by significant fluctuations in energy-related emissions. In 2020, emissions experienced a sharp decline of over 5% due to the reduction in energy demand caused by the Covid-19 pandemic. However, in 2021, emissions surpassed pre-pandemic levels, surging by over 6% in tandem with economic stimulus efforts and widespread vaccine deployment [5].

In 2022, CO2 emissions from energy combustion increased by approximately 1.3%, equivalent to 423 million metric tons, while emissions from industrial processes saw a decline of 102 million metric tons. Notably, the emissions growth in 2022 fell below the global Gross Domestic Product (GDP) growth rate of +3.2%, returning to the long-standing trend of decoupling emissions and economic growth that was disrupted in 2021. Meanwhile, improvements in the carbon intensity of energy use were marginally slower compared to the annual average of the past decade (2012-2021) [5].

Divergent trends were observed among regions and sectors. North America and Asia (excluding China) experienced an increase in CO2 emissions, outweighing reductions seen in Europe and China. Globally, CO2 emissions from the power and transport sectors, including international bunkers, grew by 261 million metric tons and 254 million metric tons, respectively, more than compensating for reductions in the industry and buildings sectors [5].

1.1 CO2 abatement technologies and the role of energy scenarios

Several technologies have emerged as potential solutions to reduce CO2 emissions across various sectors. This work explores the role of different technologies used for CO2 mitigation, assess their effectiveness, and analyze their associated costs in decarbonization scenarios. By evaluating the economic considerations, policymakers and stakeholders can identify the most cost-efficient solutions to combat climate change. Understanding the cost implications of the adoption of these technologies is indeed essential for effective decision-making and the development of economically feasible strategies to combat climate change [8].

Among the different options for the mitigation of climate change-related issues, some technological categories find large interest in the global community:

- Carbon Capture and Storage (CCS): CCS technologies involve capturing CO2 from industrial processes or power generation sources and storing it permanently underground. While CCS shows promise in reducing emissions from fossil fuel-intensive sectors, it carries significant capital and operational costs.
- Renewable Energy Sources: renewable energy sources, such as solar, wind, hydro, and geothermal power, offer carbon-free alternatives to traditional fossil fuel-based energy generation. The costs of renewable energy technologies have been declining over the years, making them increasingly competitive.
- Energy Efficiency Measures: energy efficiency measures focus on optimizing energy consumption in buildings, industries, and transportation to minimize CO2 emissions. Upgrading infrastructure, adopting energy-efficient appliances, and implementing energy management systems can significantly reduce energy demand.
- Electrification and Decarbonization of Transportation: shifting towards electric vehicles (EVs) and sustainable transportation systems is crucial for reducing CO2 emissions from the transportation sector. EV adoption is driven by factors such as battery costs, charging infrastructure development, and government incentives.
- Bioenergy and Carbon Offsetting: bioenergy technologies involve using organic matter, such as agricultural residues and dedicated energy crops, for power generation while offsetting CO2 emissions through carbon sequestration. The costs of bioenergy systems vary depending on feedstock availability, processing technologies, and carbon offset mechanisms.

Mitigating CO2 emissions requires then the widespread adoption of various technologies across all sectors.

Different sectors contribute varying amounts of CO2 emissions, including energy, transportation, industry, agriculture, and buildings. Quantifying the potential costs of reducing CO2 emissions in each sector requires a comprehensive analysis of factors such as technology availability, infrastructure requirements, and economic implications. Through robust modeling and scenario analysis, the costs associated with transitioning to low-carbon alternatives in each sector can be estimated.

Two different topics have to be taken into account:

- technological CO2 Reduction: technological advancements play a crucial role in reducing CO2 emissions. From renewable energy sources to carbon capture and storage (CCS) technologies, innovative solutions offer potential pathways for significant emission reductions. However, these technologies often involve substantial research and development costs, infrastructure investments, and operational expenses. This work will explore the economic considerations associated with adopting and scaling up these technologies.
- cost estimation methodologies: quantifying the potential costs of reducing sectoral and technological CO2 emissions requires a rigorous approach. Cost estimation methodologies may include techno-economic analysis, life-cycle cost assessments, and economic modeling. These approaches consider factors such as capital expenditures, operational costs, energy prices, and policy incentives. By combining these methodologies, policymakers and stakeholders can obtain a comprehensive understanding of the economic implications of CO2 reduction.

Some IEA analyses have examined the technologies and policies which are needed for countries and regions to achieve net-zero emissions energy systems. The World Energy Outlook 2020 examined what would be needed over the period to 2030 to put the world on a path towards net-zero emissions by 2050 in the context of the pandemic-related economic recovery [4]. The Faster Innovation Case in Energy Technology Perspectives 2020 explored whether net-zero emissions could be achieved globally by 2050 through accelerated energy technology development and deployment alone: it showed that, with respect to baseline trends, almost half of the emissions savings needed in 2050 to reach net-zero emissions rely on technologies that are not yet commercially available [4].

In the present dynamic world, it has become imperative to engage in the task of forecasting the future by constructing scenarios and exploring potential paths. Scenario analysis, as a structured process, serves as a means to characterize the future and its uncertainties. By examining different scenarios, we can delve into the "what," "how," and "if" of future trajectories, enabling us to comprehend how diverse key driving forces may lead to disparate outcomes. It is important to note that scenarios do not entail predictions or forecasts; rather, they represent a collection of potential futures that establish the boundaries of uncertainty and plausible outcomes [4].

Since the 1960s, scenario analysis has progressively gained significance in future planning. Initially employed for military purposes, scenarios later found application in public policy and emerged as a strategic management tool within the business community. Over time, this approach has disseminated to a broader audience, becoming a popular and recommended method for addressing uncertainty and enhancing decision-making processes [5]. Presently, scenario analysis is associated with a wide range of users and disciplines, including policymaking, business planning, local management, and global environmental understanding [4]. This extensive adoption has given rise to a diverse array of scenario methodologies and classifications, as evidenced by the abundant literature on scenario planning.

In this thesis, a scenario analysis based on the TIMES Model is combined with a cost estimation methodology (the marginal abatement cost curves) to evaluate the cost of emission reductions associated to particular sectors and the adopted technologies to satisfy demands for energy services.

1.2 Marginal abatement cost curves

A marginal abatement cost curve (MACC) is defined as a graph that indicates the cost, usually in $ or another currency per ton of CO2, associated with the last unit (the marginal cost) of emission abatement for varying amounts of emission reduction (in general, in million tons of CO2). Therefore, as we can see in the 1 contrasts the marginal abatement cost on the y-axis and the emission abatement level on the x-axis. A MAC curve indicates the marginal abatement cost but can also be used to determine the average cost and the total abatement cost by calculating the integral. MAC curves are not limited to the climate change problem but can be applied more generally as they essentially pull together the reduction (supply) potential of an economic bad (good) with its associated marginal cost (or the cost of the last unit) [6].

Addressing climate change requires the identification and implementation of cost-effective mitigation strategies. Marginal Abatement Cost Curves (MACCs) serve as visual representations of the cost-efficiency of various emission reduction measures. This thesis aims to provide an overview of MACCs, their construction, and their role in guiding climate change mitigation efforts.

MACCs depict the cost associated with reducing an additional unit of greenhouse gas emissions. They rank different emission reduction measures on the basis of their cost-effectiveness, allowing policymakers and stakeholders to prioritize actions that offer the greatest emissions reduction per unit of cost. MACCs consider a range of technologies, practices, and policies across sectors.

The construction of MACCs involves collecting data on the costs and emission reduction potential of various mitigation options. These options can include energy efficiency measures, renewable energy deployment, carbon capture and storage, and other low-carbon technologies. The data is plotted on a graph, with the x-axis representing the cumulative emissions reduction potential and the y-axis representing the corresponding abatement costs.

MACCs offer several benefits in the context of climate change mitigation. They provide valuable insights into the cost-effectiveness of different emission reduction measures, allowing policymakers to allocate resources efficiently. MACCs also facilitate the identification of low-cost opportunities for emission reductions, thereby supporting the development of ambitious yet economically viable climate targets. Furthermore, MACCs encourage collaboration between public and private stakeholders by fostering a common understanding of cost-effective mitigation pathways [9].

While MACCs are valuable tools, they do have certain limitations. They rely on assumptions and data inputs that may vary across regions and sectors, and the accuracy of MACCs is contingent upon the quality and availability of data. MACCs also do not consider non-economic factors, such as social and environmental co-benefits, which may be important considerations for decision-making.

MACCs have significant policy implications. Policymakers can utilize MACCs to design effective climate policies, such as carbon pricing mechanisms, subsidies, and regulations, that target sectors or activities with the greatest potential for cost-effective emissions reductions. MACCs also help inform investment decisions by identifying high-potential, low-cost technologies and practices [10].

MACCs are powerful tools for evaluating the cost-effectiveness of emission reduction measures. By visualizing the relationship between emissions reductions and associated costs, MACCs assist policymakers, businesses, and researchers in identifying the most efficient and economically viable strategies for mitigating climate change. Continued refinement and application of MACCs will contribute to the development of effective and sustainable climate policies.

To sum up, MACCs are graphical representations that illustrate the relationship between the quantity of pollution abatement or reduction achieved and the associated costs for each level of reduction. They are commonly used in environmental economics and policy analysis to assess the cost-effectiveness of different pollution control measures [11].

The MACC plots the cost per unit of pollution abatement on the vertical axis, while the horizontal axis represents the quantity of pollution abatement or reduction. It typically slopes upward, indicating that as more pollution reduction is desired, the cost per unit of reduction generally increases.

MACCs help policymakers, businesses, and researchers make informed decisions regarding pollution control strategies. By analyzing the curve, they can identify the most cost-effective approaches to achieve desired pollution reduction targets. It allows for the comparison of different abatement options and aids in determining the optimal allocation of resources for pollution control efforts.

Overall, MACCs provide a valuable tool for understanding the cost implications of pollution reduction and guiding decision-making in environmental management and policy development. There are various methodologies for calculating and constructing MACCs.

Mitigating climate change typically involves decision-making regarding technology investments and adopting a least-cost planning approach to maintain competitiveness. In the context of energy systems, this entails considering both the interaction with existing systems and the performance of discrete options. The long lifespan of many energy-related investments adds complexity to the analysis [9]. Policymakers and industries often employ Marginal Abatement Cost Curves (MACCs) as a valuable tool to assess investment options and the impact of policy measures in order to identify the least-cost options for achieving specific targets, such as climate change mitigation. MACCs are also useful for analyzing market responses to economic policies, such as the effects of the Kyoto Protocol, and evaluating policies like the Europe 2020 strategy [9].

In the study "Marginal abatement cost curves and abatement strategies: Taking option interdependency and investments unrelated to climate change into account" [9], an expert-based methodology for developing MACCs is presented, which enables least-cost investment planning when options are interdependent and influenced by factors external to the climate change discourse. While existing literature discusses the influence of path-dependency and local contexts, interdependencies are not fully considered. Major events external to climate change mitigation discourse that condition and influence the properties of the options remain relevant. The magnitude of these effects may vary across different contexts [12].

In larger energy systems such as Nordic or European power markets, changes related to individual power plants have a smaller effect compared to similar changes in district heating networks. However, aggregated changes, which are often the focus of broader MACCs, create conditions where interdependencies exist [9].

At the national level, minimizing the cost of greenhouse gas (GHG) emissions abatement is a crucial task in designing climate change policies. Similarly, profit-maximizing firms seek to identify the lowest-cost GHG abatement options. This involves considering strategies related to installed capacity, technology, and changes in production processes. MACCs have gained increased interest, in part due to reports from consulting firm McKinsey & Company [13].

MACCs have served as important tools for assessing the costs of emission reductions in the United States and the European Union, supporting recommendations by organizations like the World Bank. In the European context, MACCs are used to estimate the price of a certain amount of emission allowances within the European Union Emission Trading Scheme (EU ETS). For instance, [9] discuss an example that examines the possibility of including road transport in the EU ETS to meet abatement targets. MACCs are also employed to analyze the feasibility of different abatement options given a specific allowance price. Furthermore, MACCs are utilized for more localized assessments, such as analyzing developments in single countries, industries, and technologies. Studies analyzing marginal abatement costs without using a curve, such as cost analyses of carbon capture under different policy scenarios or optimization of natural gas combined cycle power plants, are also common.

Outside of Europe, MACCs have been applied in research on optimizing the Chinese cement industry and evaluating climate change policies in Brazil. Additionally, MACCs have been used to assess the abatement of emissions other than CO2, such as sulfur dioxide (SOx) emissions in the United States [14]. Although MACCs may be considered recent tools for evaluating climate change mitigation, their application dates back to the 1970s during the oil crises. Initially referred to as savings curves or conservation supply curves, their purpose was to evaluate energy efficiency and provide improvement options at the plant and policy levels. This approach is still employed today.

In production theory, MACCs represent the marginal loss in profit due to changed production or the marginal cost of achieving a target when a part of the process is deemed inappropriate. Since investments may yield positive financial returns, negative marginal costs are also possible. Constructing and analyzing MACCs offer insights into how to achieve a target through various options, as they correspond to the additional costs or benefits associated with actions aimed at fulfilling a specific unit of the target [9].

At the plant level, MACCs can link the emission levels of individual plants to the cost of additional emission abatement based on specific actions and technologies. In the context of CO2, MACCs are often presented with avoided CO2 emissions in metric tonnes on the x-axis and costs per reduced tonne of CO2 on the y-axis. The total cost of achieving a given target corresponds to the area under the MACC curve from zero to the target on the x-axis, demonstrating that the total cost depends on both the reduction target and the shape of the MACC.

Creating a MACC can be accomplished through either an expert-based or model-based approach, depending on the available dataset. Model-based approaches, such as the top-down approach, typically use macroeconomic models, such as the Emission Prediction and Policy Analysis (EPPA) model developed at MIT or other energy system models, to analyze the relationship between environmental policies and the impact of technical change. The top-down approach focuses on how markets respond to external pressures, such as assumed or forthcoming policy interventions, and their implications for the system. MACCs derived from this approach can cover the entire economy or be used at the industry level, considering detailed analysis of issues like policy pricing and production costs. In contrast, the bottom-up approach within the model-based framework derives marginal costs from energy system optimization models [9].

The expert-based approach, on the other hand, relies on an engineering or expert mindset that involves detailed analysis of specific options. The distinction between expert-based and bottom-up approaches varies in different reports, but all agree on the definition of the expert-based approach, which typically relies on individual estimations of particular alternatives. The aim of the expert-based approach is to identify the best available options for achieving a target within a specific context by minimizing costs [14].

From a corporate perspective, expert-based MACCs provide insights into how the market will or should adapt to policy measures and what the best available options are for future investments and actions. The expert-based approach has been the most commonly employed method in MACC analysis. When a firm is a price taker, prices are treated as fixed, reflecting the expected price scenario. Local contextual factors such as technological lock-ins, path dependency, and other barriers can influence a firm's decision-making process, potentially resulting in paths that are incompatible with the broader system [9].

Although MACCs are frequently used tools in environmental economics, their analytical properties are seldom researched outside this field. Top-down MACCs often stem from complex economic models used to predict emissions and costs under various policies, making them a compromise and less precise than empirically estimated relationships. Research in this area is growing, but detailed studies on specific technologies and their associated costs are often confidential or unpublished. The usability of MACCs depends on the assumptions underlying them, as different curves may be suitable for addressing specific questions while unsuitable for others. Expert-based MACC studies have been criticized for not fully considering systemic effects and relying on the interaction of different mitigation measures.

Marginal abatement cost (MAC) curves are a commonly used policy tool indicating emission abatement potential and associated abatement costs. They have been extensively used for a range of environmental issues in different countries and are increasingly applied to climate change policy. However, in the past, decisions in the complex field of climate policy have been partially based on MAC curves with methodological shortcomings. This work investigates how their simplistic use has been misleading and finds that the limits of the MAC curve concept can lead to biased decision making [9]. Nevertheless, MAC curves are a useful policy tool, if not relied on exclusively, providing an illustrative guide for subsequent analysis especially for iterative policy making as more information on costs and policy effectiveness is discovered. This thesis identifies some steps to overcome present short comings in the generation of MAC curves. These include a systems approach to capture interactions, consideration of ancillary benefits, a better representation of uncertainties and representation of cumulative emission abatement to address time-related interactions.

Marginal abatement cost (MAC) curves have recently become a standard policy tool in assessing the economics of climate change mitigation options. This is because they represent the complex issue of cost-effective emissions reduction in a simple manner. The complexity of climate change mitigation and the diversity of involved stakeholders makes a shorthand communication like MAC curves most useful. In addition, economic criteria have been singled out as dominant in the policy discussion. In this framing, the primary policy question is how an emission target can be achieved at least cost, while impacts on distributional equity, energy security, competitiveness effects, and secondary effects are of secondary interest.

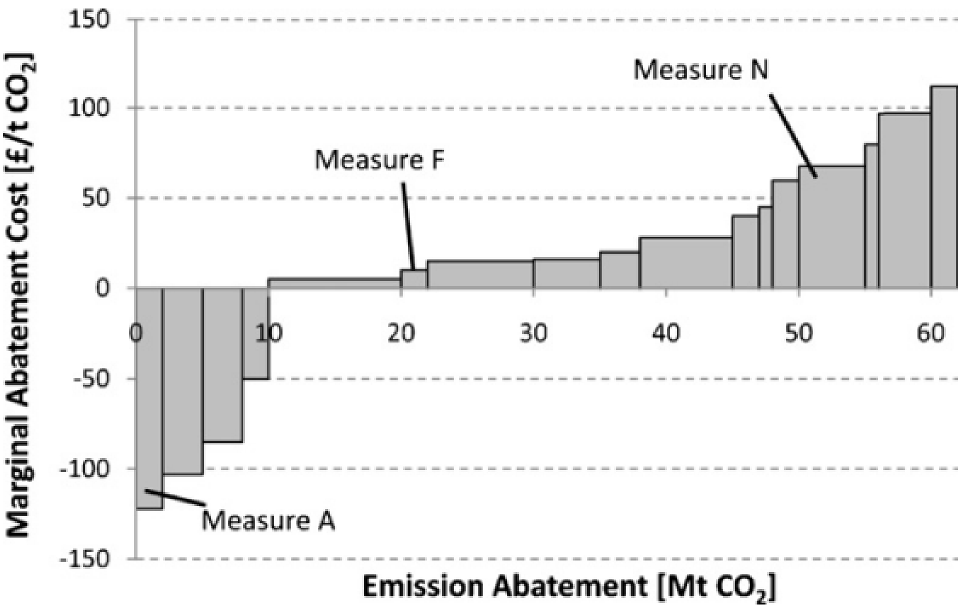

Figure 1: Example of a MAC curve [9]

The earliest utilization of MAC curves can be traced back to the early 1980s. Following the oil price crises of the 1970s, Meier (1982) developed the initial cost curves to analyze the reduction of electricity consumption in terms of cost per kilowatt-hour [$/kWh]. These curves were initially referred to as saving curves or conservation supply curves, rather than MAC curves. They swiftly became widely employed analytical tools for evaluating energy efficiency enhancements in transportation, industry, and buildings. Apart from electricity savings, another area where MAC curves found application was in assessing the potential abatement and costs of air pollutants such as sulfur dioxide (SO2) in terms of cost per kiloton [$/kt]. The early 1990s witnessed the emergence of carbon-focused curves that followed similar methodologies used in earlier cost curves for energy savings. Additionally, this concept has been employed to evaluate waste reduction [$/kg] and water availability [$\$/m^3$].

Over the past two decades, a substantial number of MAC curves pertaining to climate change mitigation have been developed. However, the proliferation of such curves has led to the challenge of policymakers encountering cost curves that are derived through diverse approaches. Two distinct approaches can be distinguished for constructing MAC curves. One option involves constructing expert-based MAC curves by individually assessing abatement measures. In this approach, the cost and emission reduction potential of each measure are evaluated in isolation and subsequently ranked from the least expensive to the most expensive. Most of the historical MAC curves mentioned earlier, as well as recent climate policy MAC curves, fall into this category. The second method involves utilizing a systems approach based on an energy model. This approach entails conducting multiple model runs with varying levels of CO2 taxes and recording the corresponding reduction in CO2 emissions. Model-derived MAC curves can be further categorized based on the type of model used, such as bottom-up models (e.g., energy system models) or top-down models (e.g., computable general equilibrium models). While expert-based MAC curves explicitly indicate in the graphical representation which measures contribute to emission reduction, this level of detail is generally omitted in model-derived MAC curves. Energy models, however, often provide the ability to present a sectoral breakdown of emissions reduction. Both approaches have their specific limitations. Model-derived MAC curves, for instance, may lack technological granularity in the graphical representation, whereas expert-based curves may not capture system-wide interactions, overlook behavioral aspects, and potentially suffer from inconsistent baselines and double counting of reduction potentials.

1.3 Literature review

In order to build a proper and complete analysis of the current state of the art, a literature review has to be done. It has been analysed and selected some of the most interesting and useful papers regarding the topic and categorized them in different ways.

Of course it's known there could be many more other works that could be analyzed for this purpose, but for the moment and for the current scope of work, the analysis done so far gives us a clear and pragmatic overview of many reports. As there are many sources and many institutions that produce such papers, it has been selected just the ones that has a history of reliability and precision like international research hubs, governative and scientific institutions and so on. We can mention at this purpose the International Energy Agency (IEA), McKinsey&Company, different Ministries of the Environment, the Goldman Sachs Group, the University of Tsinghua in Beijing, the Energy Institute in the Univercity College of London, the Statistics Norway Institute, the Environment Sciences and Engineering Department of the Lisbon University and many others.

After having read and deeply analyzed these reports, it has been noticed that some common features are present in each one of them and a classification has been done. This is very useful when we have to find papers that resembles our need, here's an example: the reports can be classified depending on their topic, or depending on their time horizon.

As a matter of fact, different types of classifications have been done, so as to have a clearer overview of all the reports and to better categorize them. So, here's the classification's classification:

1. rough classification: it's a first not detailed classification, based on just three categories, just done to first differentiate the different papers and have a first overview;
2. detailed classification: it's a specific classification that add four more categories to the first three (seven in total), bringing more precision and more details;
3. analysis classification: it's a categorization based on two different groups of papers and we'll see later these two categories; it depends on the type of analysis done in the report;
4. approach classification: also in this case it's a two categories classification, based on what kind of approach the specific report uses to deal with the topic.

Now, let's see in details each classifications.
Rough classification (1) categories:

- time horizon: it defines to which year the report do its analysis (up to 2030, 2040 or 2050);
- space horizon: it defines the geographical level of the analysis (country focused or international focused);
- level of detail: at a sectoral level, sub-sectoral level, or at a technology level.

Detailed classification (2) categories:

- time horizon: it defines to which year the report do its analysis (up to 2030, 2040 or 2050);
- space horizon: it defines the geographical level of the analysis (country focused or international focused);
- level of detail: at a sectoral level, sub-sectoral level, or at a technology leve;
- topic: the main topic analyzed in the paper;
- publication year: recent or less recent report have been analyzed;
- sectors: which sector is analyzed (transport, industry, buildings, agricolture etc);
- relevance: the importance and relevance of the report for this research (low, medium, high).

Analysis classification (3) categories:

- sectoral: in this case the paper analyzed focuses on a sectoral/sub-sectoral analysis, using a specific tool, and has a scenario as output. It is a traditional "scenario analysis" of a single or multiple sectors at national or international level;
- methodological: in this case the report does not do a traditional sectoral analysis or has a scenario as output, but instead, it focuses on a particular method or approach developed by the author to analyze the topic. It could also focus on issues or problems of an existing method, but also on the developing of a new one. So, it's a study about a specific method.

Approach classification (4) categories:

- expert based: an expert based approach is a method usually used when there is lack of data and information, necessary to build a proper work. It is based on assumptions and hypothesis that are confirmed or modified by experts and advisors that have been operating in the sector of interest for years. An important one is the Delphi method for example.
- model derived: a model derived method is an approach based on data and on a specific model use as reference to build the scenario or in any case to obtain the results expected.

Knowing these different types of classifications, we can build some tables that categorize the most important analyzed reports. Table reports the papers analyzed according to the "rough classification", while Table 2 reports the papers analyzed according to the "detailed classification".

Table 1: Summary of the analyzed paper according to the "Rough classification".

Rough classification pt.1						
Title	Authors	Time	Space	Sector	Sub-sector	Technology
Pathways to a Low-Carbon Economy	McKinsey Company	2030	World	Yes	Yes	Yes
Climate action plan 2019, To Tackle Climate Breakdown	Department of Communications, Climate Action & Environment, Government of Ireland	2050	Ireland	Yes	Yes	Yes
Marginal abatement cost curves analysis for New Zealand	Ministry for the Environment, Wellington, New Zealand	2030	New Zealand	Yes	Yes	Yes
Climate change: Everyone's business	CBI (Confederation of British Industry), Climate Change Task Force	2050	UK	Yes	Yes	Yes
Low-carbon transition pathways at the lowest cost	The department for the economy, evaluation and integration of sustainable development. Ministry of the Environment, Sea and Energy of the French Republic	2050	France	Yes	Yes	Yes
Marginal Abatement Cost Curves for U.S. Net-Zero Energy Systems	Jamil Farbes, Ben Haley, Ryan Jones. Evolved Energy Research	2050	US	Yes	Yes	Yes

Carbonomics	M. Della Vigna, E. Jones, Z. Stavrinou, A. Gandolfi, N. Snowdon, P. Young, E. Tylenda, S. Chetwode, B. Singer, D. Bingham. The Goldman Sachs Group. Inc.	2050	World	Yes	Yes	No
Levelized cost of carbon abatement cost	The Center of Global Energy policy. J. Friedmann, Z. Fan, Z. Byrum, E. Ochu, A. Bhardwaj, H. Sheeraz.	2030	US	Yes	Yes	No
The costs of mitigating carbon emissions in China: findings from China MARKAL-MACRO modeling	Wenying Chen. Global Climate Change Institute, Energy Science Building, Tsinghua University, Beijing, China.	2050	China	Yes	Yes	No
Abating greenhouse gases in the Norwegian non-ETS sector by 50 per cent by 2030	T. Fæhn, K. Kaushal, H. Storrøsten, H. Yonezawa and B. Bye. Statistics Norway.	2030	Norway	Yes	No	No
Marginal Abatement Cost Curves and Quality of Emission Reductions: A Case Study on Brazil	A. Vogt-Schilb, S. Hallegatte, C. De Gouvello. World Bank.	2030	Brazil	Yes	Yes	No

Table 2: Summary of the analyzed paper according to the "Detailed classification"

Detailed classification pt.1							
Title	Authors	Topic & comment	Publ year	Time	Space	Sectors	Relevance
Pathways to a Low-Carbon Economy	McKinsey Company	Global GHG databse, in-depth and detailed analysis of potential and costs of more than 200 GHG abatement actions. NO policy or regulatory related. Global MACC	2013	2030	World	Power, Oil&Gas, Cement, Iron & Steel, Chemicals, Transport, Buildings, Waste, Forestry, Agriculture	high
Climate action plan 2019, To Tackle Climate Breakdown	Department of Communications, Climate Action & Environment, Government of Ireland	Ireland's target for decarbonization (2030 and 2050). Well structured, state of the art analysis for each sector, actions to be taken to reach them. Irish MACC.	2019	2050	Ireland	Electricity, Enterprise and Services, Buildings, Transport, Agricolture Forestry and Land Use, Waste (Circular Economy)	high
Climate change: Everyone's business	CBI (Confederation of British Industry), Climate Change Task Force	UK options to decarbonize their sectors. Consumers, business and Government actions analyzed. McKinsey UK MACC	2007	2050	UK	Buildings, Transport, Power, Industry	high

Low-carbon transition pathways at the lowest cost	The department for the economy, evaluation and integration of sustainable development. Ministry of the Environment, Sea and Energy of the French Republic	Construction of a theoretical BAU scenario as a reference for decarb. scenarios in each sector. A bit messy	2016	2050	France	Power, Transport, Waste, Buildings, Industry, Agriculture	high
Marginal Abatement Cost Curves for U.S. Net-Zero Energy Systems	Jamil Farbes, Ben Haley, Ryan Jones. Evolved Energy Research	Description of MACC methodology. New method based on Gt of CO2 reduction over cost ranges/ton CO2	2021	2050	US	Electricity, Vehichles, Buildings+Industry, 0 carb. fuels, H2, carbon capture	high
Carbonomics	M. Della Vigna, E. Jones, Z. Stavrinou, A. Gandolfi, N. Snowdon, P. Young, E. Tylenda, S. Chetwode, B. Singer, D. Bingham. The Goldman Sachs Group. Inc.	Two global models of decarbonization by sector and technology (GS¡2.0° and GS 1.5). Very specific, too messy and chaotic	2021	2050	World	Power, Transport, Buildings, Industry, Agriculture Forestry and other land use	medium

The reports listed in the tables above are just some of those analyzed for this thesis, many others had been taken in consideration to have a better and clearer overview of the current literature and state of the art.

Now we can see the most useful ones a bit more in detail.

The "Pathways to a Low-Carbon Economy" report is a a global greenhouse gas abatement data base, developed by McKinsey Company and supported by ten leading companies and organizations across the world. The abatement data base is comprised of an in-depth evaluation of the potential, and the costs, of more than 200 greenhouse gas abatement opportunities across 10 sectors and 21 world regions, and in a 2030 time perspective [13]. This study builds on the earlier version of the global GHG abatement data base, conducted by McKinsey together with the Swedish utility Vattenfall, and published in January 2007. The current report incorporates updated assessments of the development of low-carbon technologies, updated macro-economic assessments, a significantly more detailed understanding of abatement potential in different regions and industries, an assessment of investment and financing needs in addition to cost estimates, and the incorporation of implementation scenarios for a more dynamic understanding of how abatement reductions could unfold [13]. The financial crisis at the time of writing has not been taken into account in our analysis, based on the assumption that it will not have a major effect on a 2030 time horizon. This version of the report also reflects a deeper understanding by McKinsey into greenhouse gas abatement economics, gained through conducting 10 national greenhouse gas abatement studies during the last two years. This study intentionally avoids any assessment of policies and regulatory choices. Instead, its purpose is to provide an objective and uniform set of data that can serve as a starting point for corporate leaders, academics, and policy makers when discussing how best to achieve emission reductions [13].

The "Climate change: Everyone's business" paper is a UK based analysis of all the actions the country should take to meet the 2030 and 2050 targets. A special Task Force has assessed the economic benefits and costs of different options for reducing greenhouse gas emissions. They have focused on what needs to be done by 2030 to be on track for the government's 2050 target. And its conclusion is that substantial changes will be needed in the way the economy works if the UK is to meet its goals [13]. Many of the technologies and solutions that will be required already exist but are not yet commercially viable. The pace and scale of implementation must now be accelerated. The report sends out five clear messages:

- The government's targets for 2050 are stretching but achievable and at a manageable cost – provided early action is taken. The three interdependent players are consumers, who drive change; government, which sets the framework and works with other countries to build international agreements for reducing emissions; and business, which invests and delivers.

- In the run up to 2020, the emphasis must be on much higher energy efficiency together with preparations for a major shift to low carbon energy sources in the years to 2030 and beyond. The big opportunity here is that a third of our generating capacity will become obsolete over the next 25 years, and must be replaced. This opens the way to a smaller carbon footprint.

- Technology has a vital part to play in opening up sustainable solutions. The UK has a unique opportunity to prosper in key markets of the future by taking a lead in the development of low carbon technologies and services in power, buildings, transport and industry. Government must give higher priority to existing research and technology programs in these areas, and support the launch of new programs to develop emerging solutions.

- Empowering consumers to make low carbon choices is equally vital. Business and government must work together not only to encourage take-up of greener products, but also to promote new ways of doing things (such as smarter ways of working) which can help improve our quality of life as well as cutting emissions.

- Market forces will drive big changes, but they will not by themselves be enough to do the job. The full range of public policies must be deployed to create the right incentives. Priorities include promoting an effective market price for carbon; revenue-neutral tax reform (such as changes to business rates and council tax) to reward greener behaviour; and bigger, more focused research and development (RD) programs to finance new technologies and solutions until they become commercial.

The "Climate Action Plan 2019" of Ireland is quite similar to the UK plan, that aims to set clear actions and options to abate the CO2 emissions. Sector by sector, it has been analyzed the state of the art, targets and actions that have to be taken to reach them. Here are some conclusions that came out from their study:

- power: increase RES penetration from 30% to 70% adding 12GW of renewable energy capacity (with peat and coal plants closing);

- buildings: stricter requirements for new buildings, heat pump installation, two new district heating systems

- transport: 100% of all new cars and vans being EVs by 2030 (one third of all vehicles sold during the decade will be BEV or PHEV), conversion of public transport fleets

- agriculture: expansion of forestry planting and soil management, develop sustainable and circular business models for lower carbon intensity farming

- enterprise&service: energy efficiency, replacement of fossil fuels, better management of materials and waste, carbon abatement techs in all enterprises and public services

- waste: reduction strategies for plastics and food waste, increase the quality of recycling

The "Marginal abatement cost curves analysis for New Zealand: Potential greenhouse gas mitigation options and their costs" is a marginal abatement cost curves (MACCs) analysis done by the Ministry for the Environment of the New Zeland, in collaboration with the help of Concept Consulting. This report tells us that the economic impacts of reducing emissions is a key question for policy makers in New Zealand as they consider the transition to a low-emissions economy. Considering how the economy can transition at least cost is important to minimise the impact on New Zealand's households and industries. Looking at the cost-effectiveness of individual abatement measures across the economy using a consistent framework for analysis is important to understand which measures could be explored (and in what order) to achieve a transition at the lowest cost.

The "Marginal Abatement Cost Curves for U.S. Net-Zero Energy Systems" is a paper that proposes a novel methodology for constructing marginal abatement cost (MAC) curves and presents initial results, which offers insights on the cooperative and differentiated roles of carbon abatement measures as the economy deeply decarbonizes through 2050. This new approach seeks to build on the fluency policymakers have with MAC curves by addressing some of the limitations of traditional MAC methodologies when analyzing systems that approach or achieve net-zero CO2 emissions by mid-century. The initial implementation of this new approach examines measures for reducing CO2 emissions from energy and industry in the US, but future work can adapt this analysis to incorporate more sectors and non-CO2 emission reduction measures.

"Carbonomics" is a report built by the Goldman Sachs Group and many authors, that introduce an emissions path for global net zero carbon by 2050, which would be consistent with limiting global warming to 1.5°C, with limited temperature overshoot (GS 1.5°). For this scenario, they assumed a carbon budget for remaining net cumulative CO2 emissions from all sources from 2020 to be c.500 GtCO2, consistent with the IPCC estimates in its Special Report on Global Warming of 1.5 °C (2018) - 580 GtCO2 from the 2018 base as the IPCC SR1.5 report indicates, consistent with around a 50% probability of limiting warming to 1.5 °C by 2100. They also introduce a less aspirational, but also likely more achievable global net zero model, which is consistent with the Paris Agreement's aim to keep global warming well below 2°C (GS ¡2.0°) and achieving global net zero around 2060. For the purpose of this analysis, they define the carbon budget for our GS ¡2.0° model to be near the mid-point of the range of IPCC's RCP2.6 scenario, implying a cumulative remaining carbon budget of around 750 GtCO2 from 2020. For our global net zero carbon scenarios they adopt a sectoral approach, leveraging our Carbonomics de-carbonization cost curve, and allocating the available carbon budget across different emitting industries on the basis of cost positioning and technological readiness.

"Classification and challenges of bottom-up energy system models - A review" is a paper that reviews ad classifies the different schemes used for bottom-up energy system modelling and also proposes a novel one as re-elaboration of the previous schemes. It is very usefull to have a pretty accurate classification of the different models, an moreover, this paper identifies that the main challenges of this research field rotate around four main fields: resolution in time, in space, in techno-economic detail and in sector-coupling.

The "Net Zero by 2050 - A Roadmap for the Global Energy Sector" by the International Energy Agency (IEA) maps out how the global energy sector can reach net zero by 2050, it shows that there are still pathways to reach net zero by 2050. This report sets out clear milestones, spanning all sectors and technologies, for what and when need to happen, to transform the global economy from one based on fossil fuels into one powered mainly by renewable energy. In this Summary for Policy Makers, it is outlined the essential conditions for the global energy sector to reach net-zero CO2 emissions by 2050. The pathway described in this paper is designed to maximise technical feasibility, cost-effectiveness and social acceptance while ensuring continued economic growth and secure energy supplies.

1.4 Literature analysis: industry sub-sector focus

The industry sector is composed by different sub-sectors and each of them represent a different source of emissions. we can distinguish the most relevant: chemical & petrochemical, iron & steel, paper & pulp, cement production/non-metallic minerals, other industries.
Here's a focus on some of the most impactful sub-sectors.

Cement
The cement sub-sector consists in approximately 4 percent of the total global emissions and around 11 percent of worldwide industrial emissions. China, being the largest cement producer, accounts for approximately 45 percent of the global total. Without abatement measures, cement emissions are projected to increase by 3 percent annually until 2030. This growth is primarily attributed to economic expansion, infrastructure development, and urbanization in developing nations [13]. Identified strategies for emission reduction could cut emissions by 25 percent compared to the BASE SCENARIO, and a significant portion of this abatement potential can be realized through conventional technologies. Importantly, most of these abatement measures are expected to be financially beneficial to society. However, a challenge to reducing cement emissions is the anticipated unavailability of breakthrough carbon capture and storage technology before 2020 at the earliest [13].
Cement plays a crucial role as the fundamental component in concrete, the primary building material for structures and infrastructure. Concrete stands as the second most consumed substance globally, trailing only behind water, with approximately 20 billion tonnes utilized annually by society [13]. Cement holds considerable significance for economic growth and development, emerging as a major industry across most regions worldwide. While cement production is primarily a regional industry, there is some international trade. China, propelled by its rapid economic expansion and urbanization, notably dominated cement production and related CO2 emissions, contributing to about 45 percent of global production [13]. No other region accounted for more than 10 percent of the global total. On average, a typical cement plant emits approximately 1 megaton of CO2 equivalent per year, with emissions sources concentrated within the industry [13].
The primary component of cement is clinker, an intermediate product formed through a high-temperature process involving the calcination and mineralization of limestone. Ordinary Portland cement consists of approximately 95 percent clinker and around 5 percent gypsum, finely ground into a dry powder. Depending on the application, product specifications, and building standards, clinker can be partially substituted by various mineral components, such as granulated slag from the steel industry, fly ash from coal-fired power plants, and natural volcanic materials, leading to the production of composite cements [13].
Cement production contributes to CO2 emissions in three main categories:

- Process Emissions: direct emissions from the calcination process constitutes approximately 54 percent of global cement CO2 emissions [13];

- Fuel-Combustion Emissions: direct emissions from fuel combustion accounted for around 34 percent of the total emissions [13];

- Indirect Emissions: these emissions, linked to electricity consumption, made up about 12 percent of the total emissions [13].

The most CO2-intensive aspect of the cement industry is the clinker production process, encompassing all process emissions and over 80 percent of emissions from fuel combustion. The cement industry does not produce significant emissions of other greenhouse gases. The growth in emissions is projected to be most significant in the BRIC economies (Brazil, Russia, India, and China) and the remaining regions of developing Asia and Africa. This surge is propelled by swift economic expansion, extensive infrastructure development, and urbanization. For instance, India is expected to experience an annual emissions growth rate of 8 percent, primarily attributed to the rising production of cement. Conversely, emissions growth is foreseen to be considerably slower in the developed world [13].

These are some abatement potential options feasible for the cement emission reduction:

- Increased substitution of clinker by mineral components in cement (50 percent of abatement potential, around 490 MtCO2e per year): the substitution of clinker with granulated blast-furnace slag, fly ash, and other mineral components is instrumental in reducing various emissions from clinker production, including process, fuel combustion, and indirect emissions. In the abatement scenario, the global clinker share is estimated at 70 percent, considering the regional availability of mineral components linked to actions in the steel and power sectors [13].

- Increased share of alternative fuels in the fuel mix (27 percent of abatement potential, around 260 MtCO2e per year): substituting conventional fossil fuels with alternative fuels, such as municipal and industrial waste and biomass, in cement kilns reduces direct fuel-combustion emissions. The estimated abatement potential assumes climate-neutral CO2 from biomass, attributes real emission reductions from alternative waste-disposal operations to the Cement sector, and relies on local availability of waste and biomass to replace fossil fuels [13].

- Carbon capture and storage (CCS) (22 percent of abatement potential, around 210 MtCO2e per year in net terms or around 290 MtCO2e per year at the source): CCS involves capturing CO2 from sources like cement kilns and sequestering it for permanent storage. The technology is in early development, started in 2021 for new plants and from 2026 for retrofits. By 2030, around 10 percent of total CO2 production capacity is expected to be equipped with CCS [13].

- Waste-heat recovery (1 percent of abatement potential, around 12 MtCO2e per year): utilizing excess heat from the clinker burning process for electricity generation reduces grid electricity consumption and, consequently, lowers indirect emissions [13].

- Energy efficiency improvement in clinker kilns: in the abatement scenarios, this lever is exhausted through clinker-asset renewal. Additional energy-efficiency measures beyond asset renewal are possible but not analyzed due to anticipated small potential. Clinker renewal, contributing about 210 MtCO2e of abatement, is crucial [13].

The identified abatement measures, including CCS, would eliminate 1.0 GtCO2e per year by 2030, reducing sector emissions worldwide to 2.9 GtCO2e per year—a 25 percent reduction from the BASE SCENARIO case. Nearly 80 percent of the abatement potential in 2030 relies on conventional technologies like clinker substitution and alternative fuels, excluding CCS [13].

The success of cement emissions abatement measures is contingent upon several conditions:

- Policies and Regulations: revision of cement product standards and building codes is essential, emphasizing product performance over composition to facilitate increased use of composite cements[13]. Policies should prioritize the utilization of waste co-processing in cement before considering alternatives such as incineration and landfilling [13].
- Availability of Materials: to substitute blast-furnace slag for clinker, a higher granulation rate must be achieved compared to current practices in the steel industry. The abatement scenario assumes 100 percent high-quality granulation of all blast-furnace slag from steel production [13]. Similarly, for fly ash substitution, a higher usable share than currently available from the Power sector is necessary, with the abatement potential for 2030 based on the usage of approximately 600 million tons of high-quality fly ash globally. Ensuring 25 percent of the global fuel-energy demand for the cement industry from waste collection and pre-treatment is crucial [13]. Additionally, biomass availability for 8 percent alternative fuel usage needs assurance, considering potential competition between sectors. Overall, realizing the abatement potential in the cement sector relies on supportive actions in other sectors [13].
- Avoiding Carbon Leakage: asymmetric regulations in certain regions, coupled with their absence elsewhere, could counterproductively impact Cement sector emissions [13]. This could occur if producers shift or build production capacity farther from target markets to benefit from lower production costs, despite higher transport costs. Such a scenario would result in additional emissions from increased shipping distances.
- Technology and Infrastructure: CCS technology, currently in an early development phase, must undergo testing for deployment in the cement industry by 2020. Simultaneously, there is a need for the construction of CCS transport infrastructure, including pipelines and storage capacity [13].
- Sustainable Construction: the adoption of suitable policies and practices is crucial for achieving additional indirect emission reductions. This includes promoting sustainable construction designs, building codes, and eco-efficient building materials that enhance energy efficiency in buildings and infrastructure considerably [13].

Iron & Steel

The Iron and Steel sector contributes 2.6 gigatons of CO2 equivalent per year, constituting approximately 6 percent of total global emissions and about 16 percent of worldwide industrial emissions in 2005 [13]. Out of this total, 2.1 gigatons of CO2 equivalent per year stem from direct emissions linked to iron and steel production, while 0.5 gigatons of CO2 equivalent per year are associated with power consumption. Without the implementation of abatement measures, global emissions from the Iron and Steel sector are expected to grow by 3.2 percent annually, reaching 5.6 gigatons of CO2 equivalent per year by 2030, primarily due to increased production [13]. As the largest producer of iron and steel, China is projected to represent 55 percent of global sector emissions in 2030. However, with the adoption of identified abatement strategies, emission levels can be stabilized at the 2010 level, resulting in a reduction of 1.5 gigatons of CO2 equivalent per year (27 percent) compared to the 2030 business-as-usual (BAU) case. The primary abatement levers include improving energy efficiency (the single-largest lever) and the potential use of Carbon Capture and Storage (CCS) if this technology becomes available [13].

The Iron and Steel industry is a crucial industrial sector and a key component of various other industries. The industry exhibits high fragmentation, with the top 10 companies accounting for only 25 percent of total production [13]. China is currently the leading producer, with its share expected to increase from 31 to 44 percent of global production by 2030, followed by India, Western Europe, and Russia with 15, 8, and 4 percent shares, respectively [13]. Iron and steel industry production is anticipated to more than double by 2030, primarily due to rapid economic growth and urbanization in the developing world. However, regional differences will be significant, with China forecasted to account for 179 percent of emissions growth through 2030, while the United States, Italy, Germany, and France are expected to see declines in their share of emissions by 2030 [13].

Two prevalent iron and steel production technologies are the blast furnace/basic oxygen furnace (BF/BOF, the "integrated" route) and electric arc furnace (EAF). The BF/BOF process involves reducing iron ore in the blast furnace using coke and pulverized coal injection to form hot metal, which is then treated in a basic-oxygen furnace to produce steel [13]. The EAF primarily uses scrap metal melted by high-current electricity. A third, older technology, the open hearth furnace (OHF), is still in use in the developing world, mainly in Russia and former Soviet states, but is expected to be discontinued in the next decade [13].

There are two types of carbon emissions from iron and steel production:

- Process and fuel-combustion emissions: these direct emissions, mainly from the BF/BOF process, constituted 84 percent of total iron and steel GHG emissions; [13].
- Indirect emissions: mainly related to electricity consumption in the EAF process, these emissions make up 16 percent of the total. The integrated BF/BOF process is the most CO2e-intensive, emitting around 1.6–2.8 tons of CO2 equivalent per tonne of steel, compared with about 0.6–1.8 tons of CO2 equivalent per tonne of steel for EAF steel-making, excluding after-treatment (EAF emissions depend heavily on how electricity is produced). The Iron and Steel sector emitted a total of 2.6 gigatons of CO2 equivalent annually [13].

These are some abatement potential options feasible for the cement emission reduction:

- Energy-efficiency measures (62 percent of abatement potential, 930 MtCO2e per year): this primary category contributes to 32 percent of the overall abatement potential (approximately 480 MtCO2e per year) through integrated energy efficiency measures. These measures are classified into two bundles with varying costs [13]. The more affordable bundle includes continuous improvement measures, enhanced maintenance practices, furnace insulation, optimized process flows, sinter plant heat recovery, coal-moisture control, and pulverized coal injection. The pricier bundle encompasses oxygen injection into Electric Arc Furnace (EAF), scrap preheating, flue-gas monitoring systems, improved recuperative burners, and Basic Oxygen Furnace (BOF) gas recycling [13]. Additionally, technological changes like Direct casting, integrating casting and after-treatment processes, can contribute around 3 percent of the total abatement potential (about 40 MtCO2e per year) [13]. Assuming an average energy saving of 18 percent in after-treatment energy consumption for new-build plants, and cogeneration creating a further 18 percent of the total abatement potential (around 270 MtCO2e per year), the combined effect leads to a total energy consumption improvement of 15 to 20 percent, with regional variations within this range. Smelt reduction, combining ore reduction and steel production, can contribute around 9 percent (about 140 MtCO2e per year) of abatement [13].

- Fuel shift: substituting coke with biomass-based fuel (charcoal) in Blast Furnace/Basic Oxygen Furnace (BF/BOF) furnaces can achieve 3.5 percent of abatement potential, approximately 55 MtCO2e [13].

- Process change: a more aggressive shift from BF/BOF to EAF, compared to the Business-As-Usual (BAU) case, could yield 0.3 percent or around 4 MtCO2e per year of abatement potential. This shift involves utilizing natural gas to reduce iron ore, producing Direct Reduced Iron (DRI) that substitutes for scrap in EAF furnaces [13].

- Carbon Capture and Storage (CCS) (34 percent of abatement potential, around 520 MtCO2e per year): retrofitting CCS could abate approximately 300 MtCO2e per year, and new builds around 220 MtCO2e per year [13]. CCS isolates CO2 from point sources like blast furnaces, injecting it into deep geological formations for permanent storage. The assumed capture rate for newly built steel plants is 90 percent, with 72 percent of these plants equipped with CCS in 2030. For retrofit CCS, around 40 percent of older plants are considered suitable [13]. Approximately 25 percent of all steel mills are expected to be equipped with CCS in 2030, contingent on the technology proving industrially and commercially viable [13].

For the iron and steel industry to embrace abatement measures, economic benefits must be tangible, either through direct gains or by avoiding penalties. Additionally, state-of-the-art technology must be readily available, and substantial changes in the business environment are essential for a truly transformation industry shift.

- Capturing Energy Efficiency: efforts to enhance energy efficiency and transition towards more energy-efficient processes remain focal points in the iron and steel industry. Recent studies identifying attractive energy-reduction options consistently reveal substantial potential, typically amounting to 10 to 15 percent of total energy costs, with paybacks in less than two years [13]. These efficiency improvements inherently lead to lower greenhouse gas (GHG) emissions. Organizational barriers often impede the realization of these opportunities, but in the face of cost pressures or significant energy price increases, companies are likely to pursue these net-profit-positive abatement opportunities [13].

- Significant Investment Requirements: while many companies comprehend the rationale behind adopting alternative approaches, such as direct casting for specific steel products, the associated technology changes may entail high switching costs and some level of risk [13]. Market uncertainty or tight credit conditions can further impede cash availability for large-scale investments. Positive returns over the long term are expected to drive a gradual shift to these technologies. The challenge lies in incentivizing companies to accelerate this transition [13].

- Regional Competitive Effects: current regional competitive disparities could intensify due to potential asymmetric regulations. This poses a particular challenge for companies facing competitive disadvantages as they attempt to adopt emission-reduction technologies incurring net costs. Incentive mechanisms or interventions may be necessary to facilitate essential shifts [13].

- Technologies and Infrastructure Maturity: while Carbon Capture and Storage (CCS) technology holds significant promise for emission reductions, it is still in the early stages of development and is unlikely to be ready for industry-wide implementation until at least 2025 [13].

Chemicals & Petrochemicals

The Petrochemicals sector plays a significant role in climate change, directly contributing to approximately 15 percent of global industrial greenhouse gas (GHG) emissions, equivalent to around 2.4 gigatons of carbon dioxide equivalent (GtCO2e) annually [13]. This accounts for about 4 percent of all man-made GHG emissions, including indirect emissions. Projections indicate a 122 percent increase in emissions to reach 5.3 GtCO2e per year by 2030, closely aligning with the forecasted demand growth for Petrochemicals at 3.4 percent annually. Notably, 28 percent of this growth is attributed to ozone-depleting substitutes (ODS), re [13]leased at the end of their lifecycle from downstream products like refrigeration units. Implementing identified abatement measures in the Petrochemicals industry by 2030 could lead to a substantial reduction of approximately 2.0 GtCO2e per year, marking a 38 percent decrease from the BASE SCENARIO [13]. This would result in emissions stabilizing at 3.3 GtCO2e per year, equivalent to 2015 levels. Abatement efforts in Petrochemicals involve substantial upfront investments but offer significant and increasing operational-cost savings through reduced energy needs and rising energy prices. China, with its prominent position in chemicals production and high emission intensity, holds both the highest share of emissions and a substantial portion of the abatement potential, approximately 40 percent [13].
Over the past 15 years, the chemicals industry has made considerable strides in reducing its GHG-emissions intensity. Despite a 3.2 percent annual growth in chemical-industry volumes since 1990, emissions have increased by only 1.7 percent annually [13]. This improvement can be attributed to enhanced energy efficiency, debottlenecking, improved asset utilization, and other proactive measures aimed at curbing GHG emissions. However, regional variations exist, with Europe and North America showing minimal or no absolute emissions increases, while developing countries and other regions have experienced significant emissions growth, largely driven by robust volume expansion [13].

If we continue with this path. Petrochemical sector emissions are projected to grow at an annual rate of approximately 3.2 percent until 2030 [13]. This growth is driven by both robust production expansion and a shift in production to regions with higher carbon intensity, notably China. China is expected to increase its share of global chemicals production from 27 percent in 2005 to 34 percent in 2030 [13].
The rapid decarbonization observed in recent years within chemicals production is not anticipated to continue at the same pace due to diminishing marginal effects of efficiency measures and the shift of production to Asia, where coal becomes a more prevalent primary fuel [13]. Looking forward, an annual decarbonization rate of only 0.2 percent is considered achievable unless more aggressive actions to reduce the carbon footprint of the chemicals industry, as outlined in this report, are undertaken [13].

Chemicals industry emissions can be categorized into three main groups:

- Process emissions: direct releases during the production process, accounting for around 40 percent of total chemicals emissions. Future emissions are projected to grow in proportion to production volumes [13]. A significant portion of these emissions is linked to ozone-depleting substitutes (ODS) used as replacements for hydrochlorofluorocarbons (HCFCs), particularly in refrigeration applications. Abating these emissions requires improved recycling initiatives rather than direct control by the Chemicals industry [13].

- Direct emissions from fuel combustion: accounting for about 26 percent of the global emissions, these result from generating heat and/or electricity at the production site. Future emissions are assumed to align with production forecasts, considering LOW BASE SCENARIO measures [13].

- Indirect emissions from electricity consumption: contributing approximately 34 percent of the emissions, these result from the Power Generation sector but are caused by the Chemicals industry through electricity consumption [13].

The identified abatement measures for the Petrochemicals sector can be grouped into four categories, each contributing to the reduction of greenhouse gas (GHG) emissions:

- Energy Efficiency: This category, accounting for about 1,100 million metric tons of CO2 equivalent (MtCO2e), represents 55 percent of the total abatement potential [13]. Energy-efficiency measures, such as improvements in motor systems, combined heat and power (CHP), enhancements in ethylene cracking, and catalyst optimization, are key contributors. Most measures in this category are not only environmentally beneficial but also economically advantageous [13].

- Fuel Shift: Approximately 320 MtCO2e, or 16 percent of the total abatement potential, can be achieved through a shift toward alternative and cleaner fuels [13]. This involves transitioning from oil to gas and from coal to biomass. The measures in this category are relatively cost-effective or offer a net benefit to society. Aggressive efforts in fuel shifting could lead to replacing about 50 percent of the current coal usage with biomass by 2030, considering the global demand and supply dynamics [13].

- Carbon Capture and Storage (CCS): CCS in the chemicals industry is estimated to contribute around 420 MtCO2e, representing approximately 21 percent of the total abatement potential [13]. CCS is an innovative technology that captures CO2 after its emission from a point source during the production cycle, storing it in subterranean formations. Two applicable CCS technologies in the Petrochemicals sector include capturing a pure CO2 stream from ammonia production and capturing CO2 from fuel-combustion emissions, similar to CCS in the Power Generation sector [13].

- Decomposition of Non-CO2 GHG Gases: The destruction of highly potent greenhouse gases (GHGs) constitutes around 8 percent, or 150 MtCO2e, of the abatement potential in the Petrochemicals sector. Measures in this category involve the decomposition of N2O generated in the production of common chemicals like nitric acid and adipic acid [13].

2 Methodology

Since the early 1970s, a wide range of models has become available for the analysis of energy systems or subsystems, such as the power system. These models serve various purposes, including improving the design of energy supply systems based on demand forecasts, enhancing understanding of present and future demand-supply interactions, exploring energy and environment interactions, studying energy-economy interactions, and facilitating energy system planning [2].

As stated by Hoffman and Wood (1976), "energy system models are formulated using theoretical and analytical methods from several disciplines including engineering, economics, operations research, and management science." Consequently, these models employ different techniques, such as mathematical programming (particularly linear programming), econometrics, statistical analysis, and network analysis [2]. Consequently, energy system models vary in terms of their data requirements, technology specifications, skill prerequisites, and computational demands. Some models are highly detailed, requiring extensive databases that may not be readily available in developing countries [2].

The skill and computational requirements of certain models can be too burdensome for developing countries, where there may be a shortage of skilled human resources. Most of these models were developed in industrialized countries to address specific issues or problems within specific contexts. While some of these models have been applied in developing country contexts, transferring modeling technologies to these countries is challenging [2]. The literature contains only a limited number of models developed in developing countries that have not crossed national boundaries to create a broader portfolio of modeling tools for developing countries. Given the diversity of models in terms of their purpose, philosophy, features, capabilities, potential overlaps, and data demands, it is crucial to develop a comparative understanding of these models while considering the specific characteristics of developing countries [2].

The scope of an energy system model can vary depending on its purpose and focus. At one extreme, engineering models cover specific components or sub-components, while comprehensive models encompass energy-economy interactions at the national and international levels. In [2] review, it's excluded both of these types, as they either extend beyond the energy sector by including energy-economy interactions or focus exclusively on one specific component or sub-component. Our focus is on integrated models that cover the energy sector and its sub-sectors, considering both the supply and demand sides. However, given the diversity of technologies and the complexity of the energy sector, some models specifically concentrate on a particular aspect of a sub-sector, such as electricity, coal, or gas. These models may or may not encompass both the supply and demand sides of the sub-sector [2]. Similarly, while many models cover multiple fuels, some exclusively focus on the supply side, while others solely examine the demand side.

2.1 The TIMES model generator

The TIMES (The Integrated MARKAL-EFOM System) model generator was developed as part of the IEA-ETSAP's methodology for energy scenarios to conduct in-depth energy and environmental analyses [10]. The TIMES model generator combines two different, and complementary, approaches to modelling energy: a technical engineering approach and an economic approach. In a nutshell, TIMES is used for, "the exploration of possible energy futures based on contrasted scenarios" [10].

TIMES models encompass all the steps from primary resources through the chain of processes that transform, transport, distribute and convert energy into the supply of energy services demanded by energy consumers [10]. On the energy supply-side, it comprises fuel mining, primary and secondary production, and exogenous import and export. The "agents" of the energy supply-side are the "producers". Through various energy carriers, energy is delivered to the demand-side, which is structured by sectors including the residential, commercial, agricultural, transport and industrial sectors. The "agents" of the energy demand-side are the "consumers". The mathematical, economic and engineering relationships between these energy "producers" and "consumers" is the basis underpinning TIMES models.

All TIMES models are constructed from three basic entities [10]:

- Technologies (also called processes) are representations of physical devices that transform commodities into other commodities. Processes may be primary sources of commodities (e.g. mining processes, import processes), or transformation activities such as conversion plants that produce electricity, energy-processing plants such as refineries, end-use demand devices such as cars and heating systems, etc.
- Commodities (including fuels) are energy carriers, energy services, materials, monetary flows, and emissions; a commodity is either produced or consumed by some technology.
- Commodity flows are the links between processes and commodities (for example electricity generation from wind). A flow is of the same nature as a commodity but is attached to a particular process, and represents one input or one output of that process.

These three entities are used to build an energy system that characterizes the country or region in question. All TIMES models have a reference energy system, which is a basic model of the energy system before it is substantially changed either for a particular region or for a particular scenario.

The principle insights generated from TIMES are achieved through scenario analysis. A reference energy scenario is generated first by running the model in the absence of any policy constraints. These results from the reference scenario are not normally totally aligned to national energy forecasts (generated by simulating future energy demand and supply), mainly because TIMES optimizes the energy systems providing a least cost solution.

A second scenario is then established by imposing a (single of many) policy constraint on the model (e.g. minimum share of renewable energy, maximum amount of GHG emissions or minimum level of energy security) and the model generates a different least cost energy system with different technology and fuel choices. When the results are compared with those from the reference scenario, the different technology choices can be identified that deliver the policy constraint at least cost.

Once all the inputs, constraints and scenarios have been put in place, the model will attempt to solve and determine the energy system that meets the energy service demands over the entire time horizon at least cost. It does this by simultaneously making equipment investment decisions and operating, primary energy supply, and energy trade decisions, by region. TIMES assumes perfect foresight, which is to say that all investment decisions are made in each period with full knowledge of future events. It optimizes horizontally (across all sectors) and vertically (across all time periods for which the limit is imposed).

The results will be the optimal mix of technologies and fuels at each period, together with the associated emissions to meet the demand. The model configures the production and consumption of commodities (i.e. fuels, materials, and energy services) and their prices; when the model matches supply with demand, i.e. energy producers with energy consumers, it is said to be in equilibrium. Mathematically, this means that model maximizes the producer and consumer surplus. The model is set up such that the price of producing a commodity affects the demand for that commodity, while at the same time the demand affects the commodity's price. A market is said to have reached an equilibrium at prices p and quantities q when no consumer wishes to purchase less than q and no producer wishes to produce more than q at price p. When all markets are in equilibrium the total economic surplus is maximized (i.e. the sum of producers' and consumers' surpluses) [10]. This is represented graphically in Figure 2.

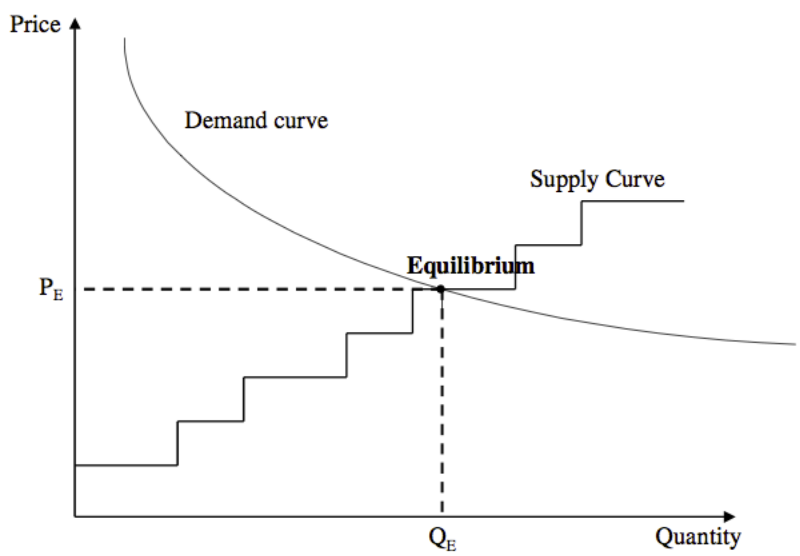

Figure 2: Achieving market equilibrium in TIMES [10].

The main output TIMES are energy system configurations, which meet the end-use energy service demands at least cost while also adhering to the various constraints (e.g 80% emissions reduction, 40% renewable electricity penetration). In the first instance, TIMES model addresses the question: is the target feasible? If an energy system is possible, it can then be examined, at what cost? The model outputs are energy flows, energy commodity prices, GHG emissions, capacities of technologies, energy costs and marginal emissions abatement costs.

Bottom-up models, such as models of the TIMES family, are renowned for their extensive technological detail and are employed to analyze the entire energy sector at various scales, including regional, national, or global levels. Bottom-up models consider a range of technological components, as illustrated in red in Figure 3. These components comprise conversion processes such as coal processing, refineries, power plants, and combined heat and power (CHP) plants, as well as corresponding distribution processes like gas networks, transportation systems, and district heat networks. The primary energy derived from domestic sources and imports is indicated in blue. The final user categories are presented in orange and include industry, commercial and tertiary sectors, households, and transportation. Finally, the various services provided by energy, such as process energy and heating, are highlighted in green.

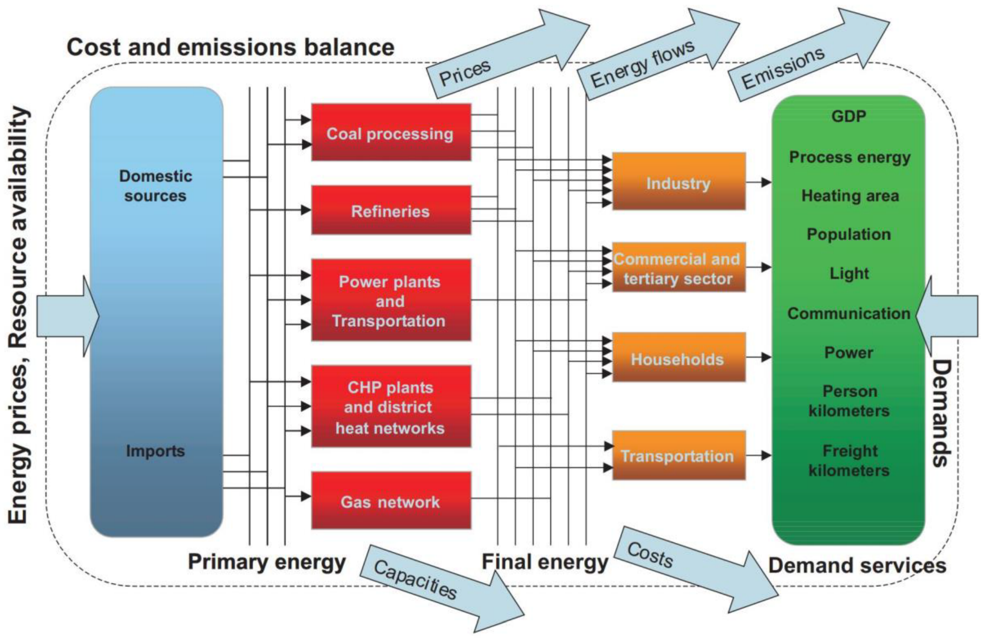

Figure 3: A schematic of a bottom-up model used at the national scale. The inward pointing arrows indicate the inputs to the model while the outward pointing arrows show the outputs [10].

Bottom-up models are commonly employed alongside multi-period optimization schemes to facilitate strategic planning and policymaking processes. The optimization problem can be defined as follows: given a set of end users with their forecasted energy service demand over a specified long-term time horizon, a range of potential primary energy sources, and corresponding conversion and distribution technologies, determine the optimal configuration of the energy system that minimizes overall costs or maximizes overall efficiency while ensuring that energy demand is met by supply in each time period.

Typically, time horizons spanning several decades are considered, encompassing both existing technological components and potential future technologies that may arise from investments. The temporal resolution of the model should be sufficient to capture variations in daily energy demand as well as seasonal fluctuations. To achieve this, bottom-up models divide the time horizon into multiple time slices, such as summer day, summer night, winter day, and winter night, ensuring that energy supplied matches the quantity demanded at each time slice. Therefore, the fundamental principle of bottom-up models lies in the market clearing condition, along with the fulfillment of energy balance by each technological component. Solving the multi-period optimization problem reveals the optimal configuration of the national energy system, including the optimal mix of primary energy sources and the optimal selection of current and future conversion and distribution technologies. Additionally, the model can be extended to incorporate sustainability criteria by quantifying the emissions associated with each technological option. Introducing an emissions penalty into the objective function enables the identification of a long-term energy system configuration that optimizes the trade-offs between economic and environmental factors.

Bottom-up models offer several advantages due to their high level of technological detail. Firstly, they allow for the inclusion of new breakthrough technologies, enabling the study of their potential impact and market penetration. Consequently, bottom-up models provide a plausible roadmap for the adoption of these new technologies, which can inform policymaking decisions. Moreover, these models possess explanatory power, aiding in the understanding of the underlying causes of certain outcomes. However, the substantial amount of data required and the computational costs associated with bottom-up energy models present drawbacks. Additionally, the mechanistic nature of bottom-up approaches implies a limitation in capturing factors that are difficult to describe or predict, such as human agency.

The most widely used bottom-up models include the MARKAL (MARket ALlocation) family of models developed by the International Energy Agency's Energy Technology Systems Analysis Program (IEA-ETSAP) and the MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impacts) family of models developed by the International Atomic Energy Agency (IAEA) and the International Institute for Applied Systems Analysis (IIASA). The MARKAL models have been employed by over 250 institutions in 70 countries for various purposes, such as economic analysis of climate policies and studies on the potential of hydrogen fuel cells and nuclear power. The MESSAGE family of models has been expanded with additional modules, including a macro-economic module, a climate module, an air pollution module, and an agriculture and forestry module, to form the IIASA Integrated Assessment framework. Integrated Assessment Models (IAMs) are suites of tools that integrate knowledge and data from various disciplines, such as climate change modeling, energy economics, social studies, forestry, and agriculture, to support decision-making in public policy. To ensure computational tractability, IAMs often employ high levels of technological aggregation, typically at the national or global scale. Recognizing the profound implications of energy models on public policy, several open-source models have been developed. Initiatives like the open energy modeling initiative and the OSeMOSYS framework, extended for a global system boundary, have contributed to the availability of open energy system models. Open energy system models offer the additional advantage of transparency when utilized in the formulation of public policies.

The top-down approach, in contrast, encompasses the modeling of all sectors within the entire economy. Given that energy serves as an input to virtually every other sector, top-down energy system models aim to capture the interconnections and feedback that would not be captured through a bottom-up analysis. For instance, growth in industrial sectors, such as the steel industry, may correspond to increased energy demand and higher energy prices. However, any productivity improvements in the industrial sector can also lead to reduced energy generation costs and lower energy prices. Therefore, modeling the interaction between the energy sector and other economic sectors is valuable in elucidating the often counter-intuitive impacts on the overall economy resulting from specific decisions made in the energy sector, and vice versa. Considering the significant influence of energy on other sectors, analyzing such interconnections becomes particularly relevant for energy systems.

Furthermore, energy system decision-making is closely linked to sustainability considerations, necessitating analysis with broader system boundaries and a higher level of technological aggregation, as discussed in Section 3.2. These factors make top-down models well-suited tools for informing general policymaking at regional, national, or global scales, including policies related to taxation, energy subsidies, or climate change. The advantages of top-down models lie in their ability to consistently account for the entire economy. However, they also have limitations, such as providing generalized results without extensive explanatory power, inadequate incorporation of technological progress, and insufficient detail at smaller scales due to the utilization of highly aggregated empirical data.

2.2 The TIMES graphic user interface: VEDA

The VEDA tool has been used to do the analysis and to run and test the different scenarios coming from the TIMES-Italy model.

VEDA FE and VEDA BE are powerful tools required by complex mathematical and economic models for handling data input and smart exploration of the results created by such models and the creation of reports. VEDA is under continuous development, driven by a strong desire to keep increasing the efficiency and transparency of managing input and output of data-intensive models.

VEDA is a powerful yet user friendly set of tools geared to facilitate the creation, maintenance, browsing, and modification of the large data bases required by complex mathematical and economic models. Also, smart exploration of the results created by such models and the creation of reports. The VEDA system is composed of two major subsystems - VEDA Front-End (VEDA_FE) and VEDA Back-End VEDA_BE).

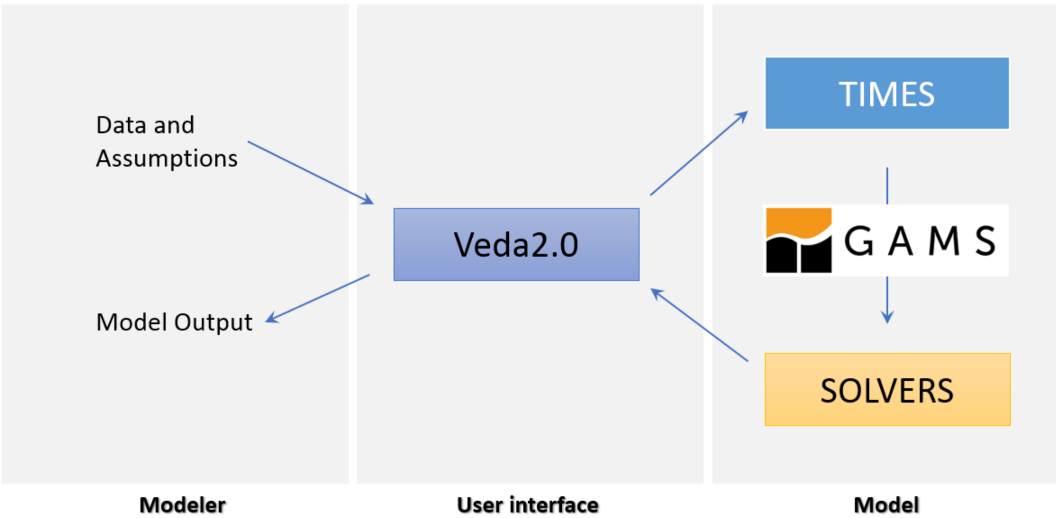

Figure 4: Overview of the VEDA system for TIMES modeling.

Data and assumptions are fed into VEDA that provides input to the TIMES code. VEDA accepts input from a variety of Excel files with different (flexible) structures that are tailored to work efficiently with data intensive models. The TIMES code works in the GAMS environment and produces text output that is read by VEDA. VEDA produces numerical and graphical (mainly via Excel) output for the user.

2.3 Procedure for the calculation of MACCs

Several scenarios are generated in TIMES-Italy with the support of the VEDA_BE and VEDA_FE graphic user interface. The scenarios analyzed in this work share the same technological database and the same set of constraints, except for those regarding CO2 emissions. Indeed, different decarbonization scenarios are taken into account.

A decarbonization scenario refers to a hypothetical and systematic plan or pathway designed to reduce or eliminate carbon dioxide (CO2) emissions from a particular system, sector, or the entire economy. The primary goal of a decarbonization scenario is to transition from carbon-intensive practices, such as the burning of fossil fuels, to cleaner and more sustainable alternatives.

Decarbonization scenarios are often developed in the context of addressing climate change and mitigating its impacts. They involve strategic measures to significantly reduce greenhouse gas emissions, with a particular focus on CO2, which is a major contributor to global warming.

In this work, several scenarios considering different levels of CO2 emissions reduction are analyzed. The first kind of scenarios analyzed in this work is the so-called "reference scenario" ("BASE"), where no CO2 constraints are applied. Starting from the outcomes of the BASE scenario, in particular for the last year of the analysis, i.e. 2050, different decarbonization scenarios, indicated by the acronym "MACCxx", where "xx" represents the percentage of CO2 emissions reduction with respect to the base case, are generated, up to 80% reduction, which is very close to a net-zero emissions scenario.

Since each decarbonization scenario with growing abatement targets requires larger mitigation efforts, and each technology to be used in the energy sector is characterized by different costs, a MAC curve can be generated from the outcomes of the model to identify the most difficult, i.e. costly, sectors to decarbonize and provide quantitative indications on what to expect in the development of the energy system. Indeed, at each step, more expensive technologies will be used which allow a higher degree of decarbonization with respect to the previous step.

Another important topic to understand is the abatement cost that refer to the additional expenses incurred when adopting a low-emission technology compared to the standard scenario, typically measured in euros per metric ton of CO2 equivalent emissions abated. These costs include both the annualized capital and operational expenditures associated with implementing the low-emission technology, representing the total 'project cost' for its installation and operation. Notably, the availability of capital is not regarded as a limiting factor [13].
One of the example of the abatement cost formula can be considered the one included in the [13]. The calculation of abatement costs follows the formula outlined below. It includes the entire expense of adopting a CO2 equivalent efficient alternative, including investment costs amortized over the asset's lifespan, operational expenses covering personnel and materials, as well as potential cost savings resulting from the alternative's use, particularly in terms of energy efficiency. However, it excludes transaction costs, communication/information costs, subsidies or explicit CO2-related expenses, taxes, or broader economic implications such as advantages stemming from technological leadership [13].

The abatement cost is a critical factor in decision-making processes related to climate

$$\text{Abatement cost} = \frac{[\text{Full cost of } CO_2\text{e efficient alternative}] - [\text{Full cost of reference solution}]}{[CO_2\text{e emissions from reference solution}] - [CO_2\text{e emissions from alternative}]}$$

Figure 5: Abatement cost formula.

change mitigation. It helps policymakers, businesses, and organizations assess the economic feasibility of different emission reduction measures and prioritize those that provide the most cost-effective solutions. The goal is to identify interventions that achieve emission reductions at the lowest possible cost, ensuring that efforts to combat climate change are cost effective [13].
The abatement cost curve is a common tool used in the field of environmental economics. This curve illustrates the relationship between the quantity of emissions reduced and the associated cost for different abatement measures. It helps stakeholders identify low-cost options for emission reduction and understand the trade-offs between economic considerations and environmental benefits [13].
Key considerations in evaluating abatement costs include the scalability of the measures, technological advancements, regulatory frameworks, and the specific characteristics of the industry or sector. Understanding abatement costs is crucial for designing effective climate policies, setting emission reduction targets, and promoting the adoption of sustainable practices without disproportionately burdening economies [13].

3 Results

The runs performed in TIMES-Italy for the different scenarios ranging from the "BASE" to the "MACC80" provide results for the decarbonization trajectory starting from the base year (2006) to the end of the time scale, i.e. 2050.

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Base Scenario

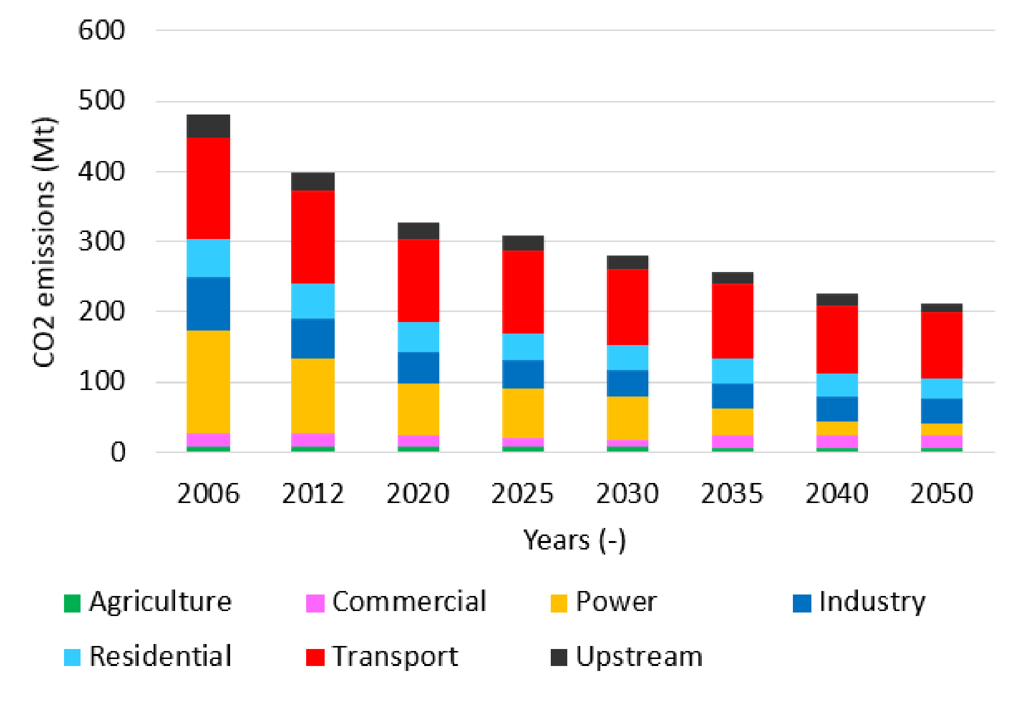

Figure 6: Base scenario: emissions trajectory up to 2050 for the different sectors..

The emissions trajectory in the "BASE" scenario in 6 shows the behaviour of the CO2 emissions up to 2050 in the absence of constraints on CO2 emissions. Despite this assumption, total emissions are reduced by more than 30% in 2050 with respect to 2030. The sectors having the larger impact on the total emissions throughout the model time scale are the electricity and the transport sectors. However, the power sector experiences almost 80% reduction in CO2 emissions from 2020 to 2050, while emissions from the transport sector are reduced by just 20% in the base scenario. Generally speaking, total emissions are just reduced by 35% in 2050 with respect to 2020, reaching 212 Mt by 2050. This is therefore the starting value for the application of the emissions reduction constraints in "MACCxx" scenarios.

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MACC10 Scenario

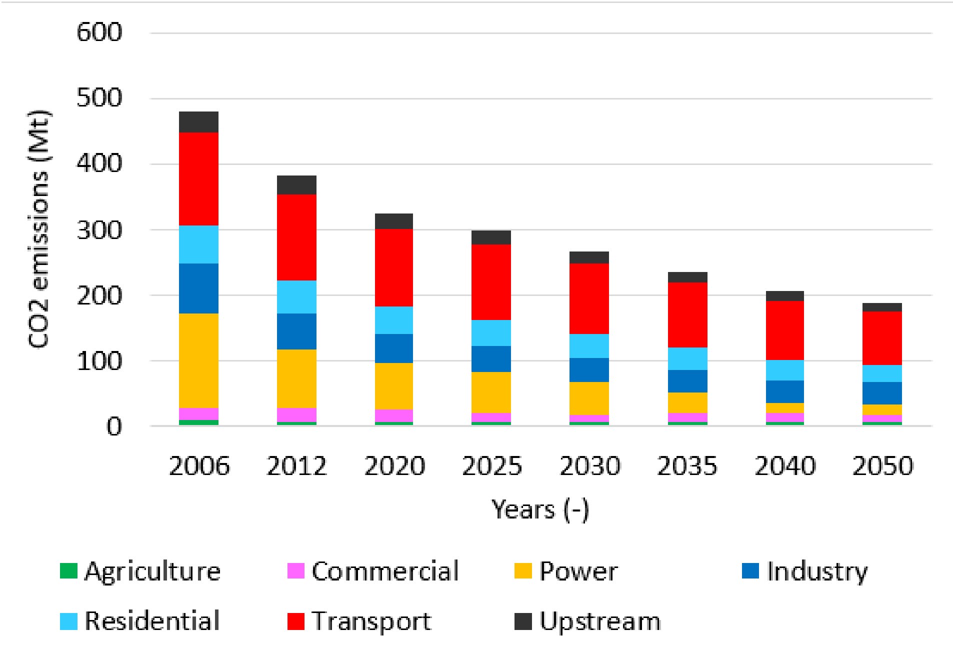

Figure 7: MACC10 scenario: emissions trajectory up to 2050 for the different sectors..

In the MACC10 scenario (see Figure 7), the trajectory for emissions reduction is quite similar to the BASE scenario, except for the situation in 2050. Indeed, emissions from the commercial sector experience the larger reduction with respect to base with -34%, making it the easiest one to be further decarbonized, even though reductions below 15% are experienced also in the power, residential and transport sector. Industry keeps the same levels as in the BASE scenario, calling for high costs required for a further abatement of CO2 emissions in it.

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MACC20 Scenario

The MACC20 scenario in (see Figure 8) shows relatively small differences with respect to the previous one, with just the power sector and transport experiencing significant reductions around 14% with respect to the MACC10 in 2050.

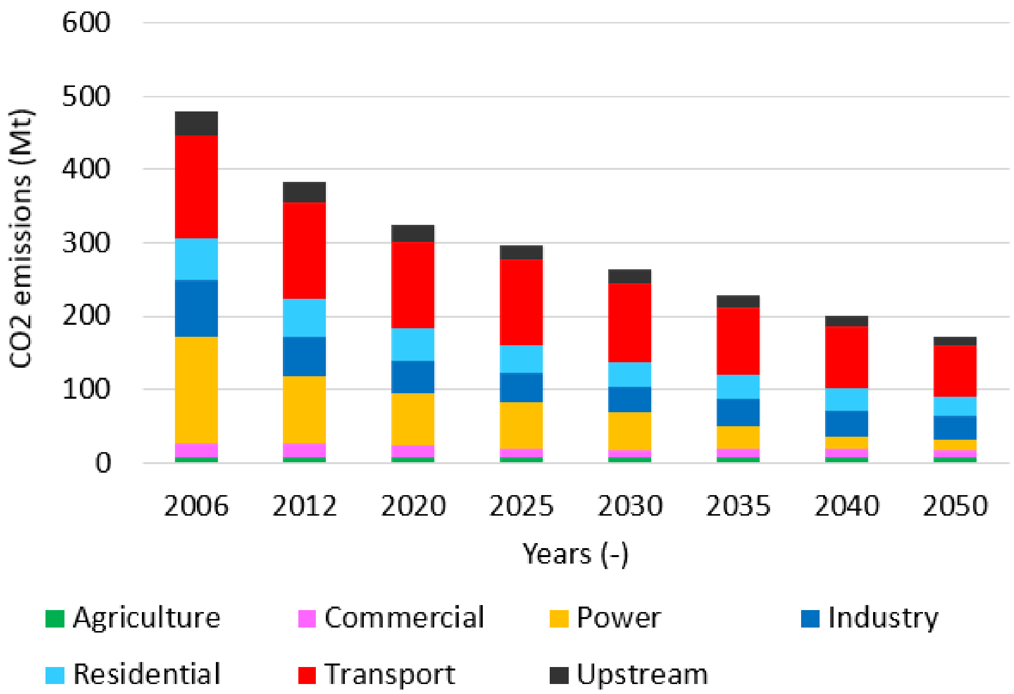

Figure 8: MACC20 scenario: emissions trajectory up to 2050 for the different sectors.

The MACC20 scenario in (see Figure 8) shows relatively small differences with respect to the previous one, with just the power sector and transport experiencing significant reductions around 14% with respect to the MACC10 in 2050.

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MACC30 Scenario

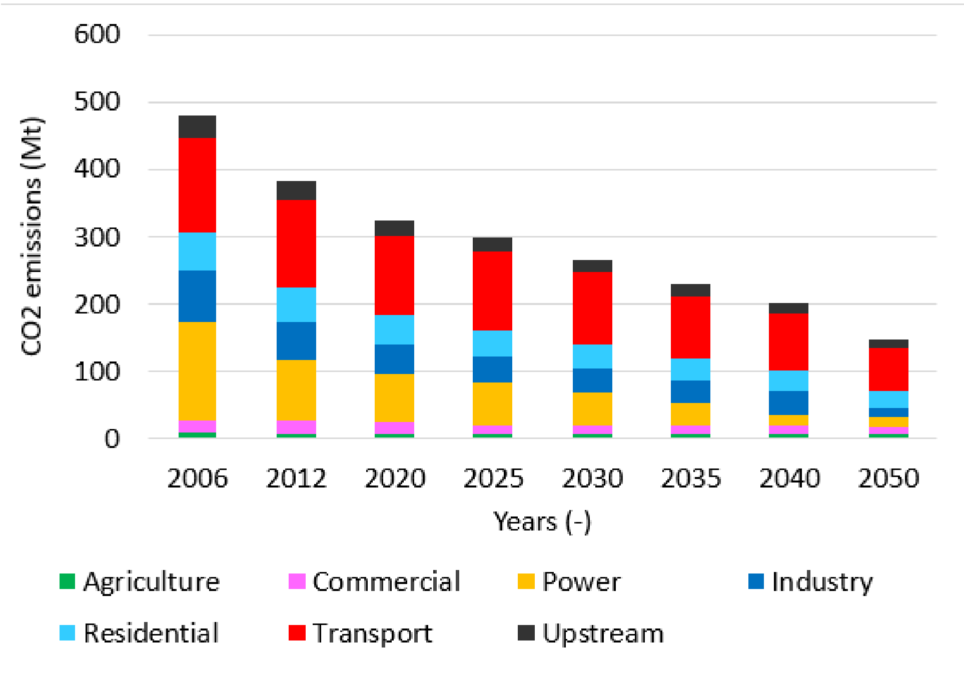

Figure 9: MACC30 scenario: emissions trajectory up to 2050 for the different sectors.

The situation changes radically in the MACC30 scenario in Figure 9. Indeed, carbon capture and storage technologies appear here to bring net total emissions to 148 Mt in 2050. In particular, they allow industrial emissions to be halved with respect to the MACC20 scenario in the last time period, while also showing further emissions reductions in the commercial sector (-23%) and in the residential sector (-9%).

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MACC40 Scenario

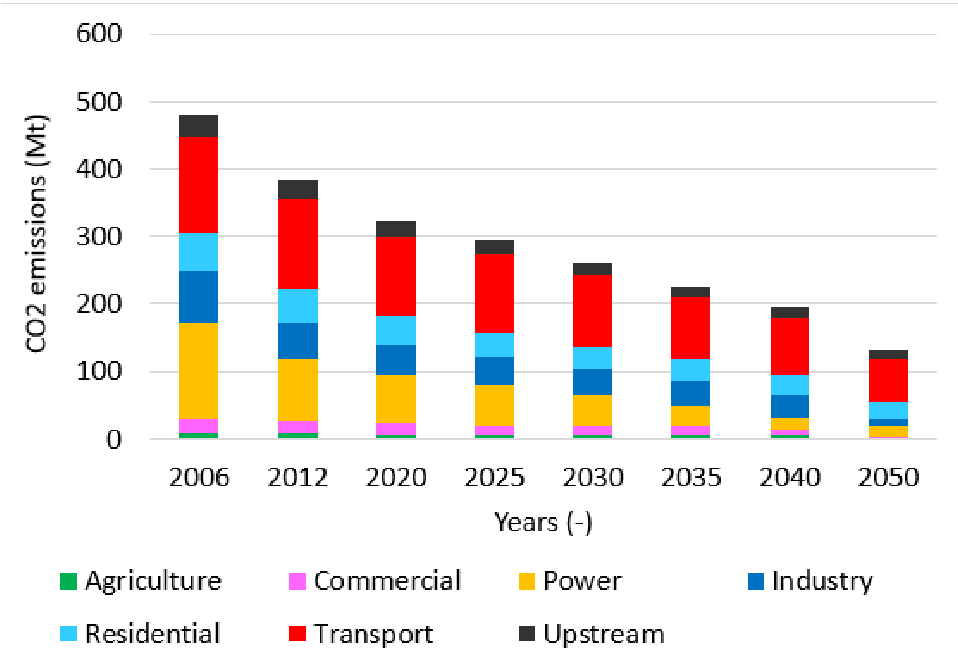

Figure 10: MACC40 scenario: emissions trajectory up to 2050 for the different sectors.

The adoption of CCS in the industrial sector is again significant in the MACC40 scenario in Figure 10, allowing 30% further reduction with respect to MACC30 in 2050. That is translated into 18 Mt of CO2 emissions less than in MACC40, with significant reductions especially in the commercial sector, with -67%. Moreover, in this scenario emissions from the agricultural sector are almost nullified with a -85% in 2050 with respect to the previous scenario, even though the impact of such sector is not that relevant on the overall emissions (2% already in 2020).

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MACC50 Scenario

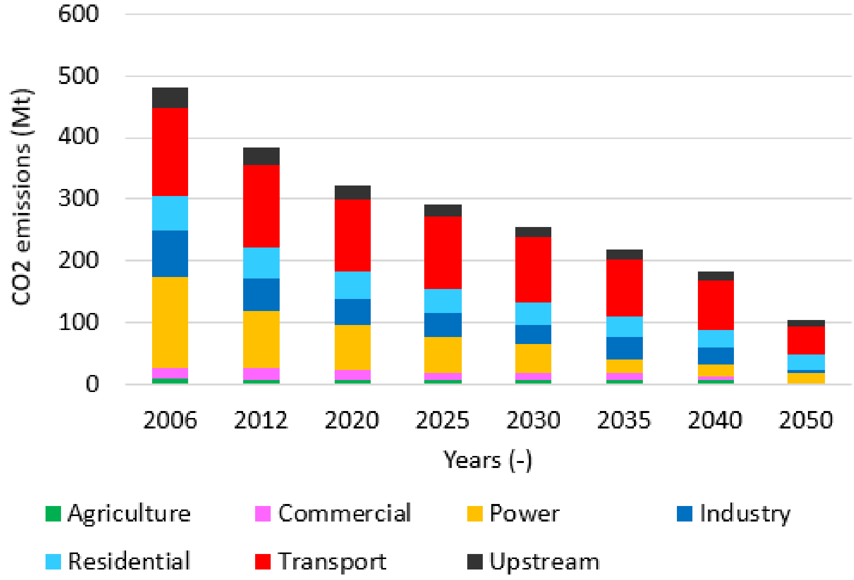

Figure 11: MACC50 scenario: emissions trajectory up to 2050 for the different sectors.

In MACC50 in Figure 11 the emissions from the agricultural sector are eventually brought to zero, while all the other sectors experience significant reductions with respect to the previous scenario. Indeed, emissions from the industrial and the transport sectors are reduced by almost 30%, even though the adoption of CCS is still relevant in the former only at the end of the time scale. Also the power sector resorts to CCS but in lower measure, and is able to achieve 8% reduction with respect to MACC40. A significant CO2 emissions decrease is experienced in the commercial sector (-25%), while the residential and the upstream sector observe a -5% reduction.

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MACC60 Scenario

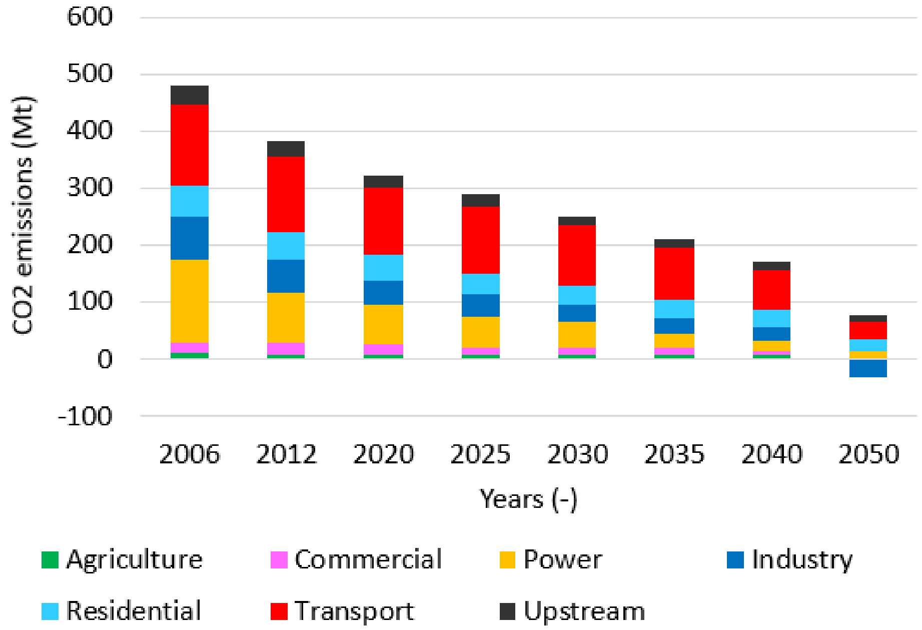

Figure 12: MACC60 scenario: emissions trajectory up to 2050 for the different sectors.

Starting from MACC60, the adoption of CCS in the industrial sector even allows to reach negative emissions in it (-33 Mt with respect to 7 Mt in MACC50, see Figure 12). A further, deep decarbonization is experienced in the last time step also in the transport sector (-36% with respect to MACC50) and in the commercial sector (-46%), but generalized reductions are visible in all sector, even if at lower rates. Net total emissions reach 42 Mt, making this very close to a net-zero emissions scenario.

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MACC70 Scenario

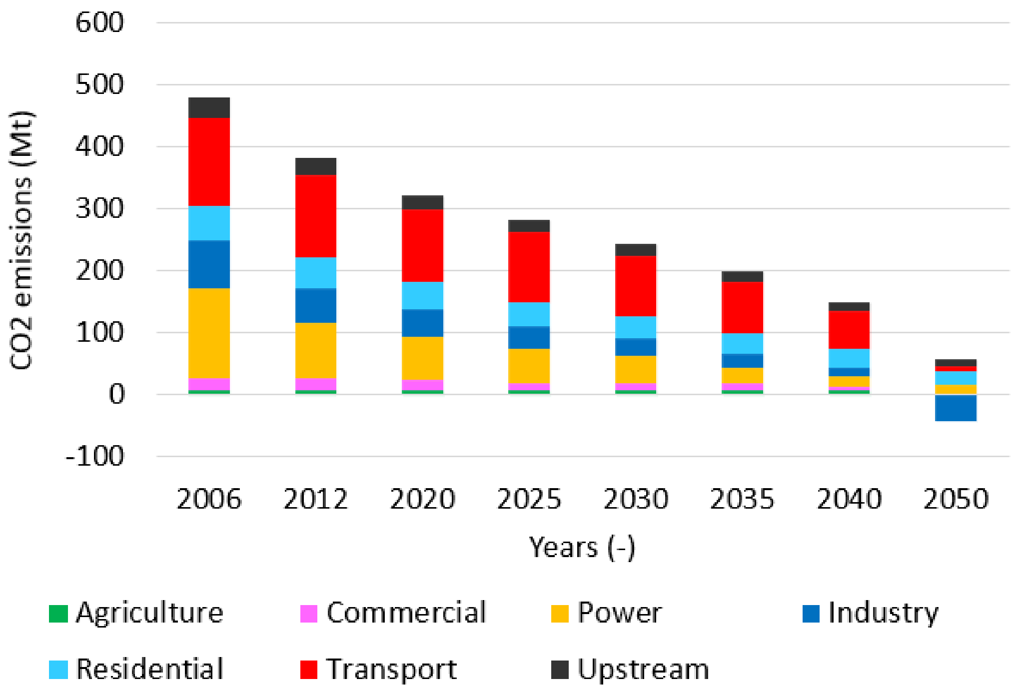

Figure 13: MACC70 scenario: emissions trajectory up to 2050 for the different sectors.

In MACC70 (see Figure 13), the only relevant sectorial contribution to total emissions reduction with respect to the previous scenario is given by the transport sector (-70% in 2050), while surprisingly the power and industrial sector experience a ∼+30% rebound. Such result is highly significant because it highlights how reductions in the transport sector are delayed as much as possible, reflecting the very high costs related to the transformation of such sector.

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MACC80 Scenario

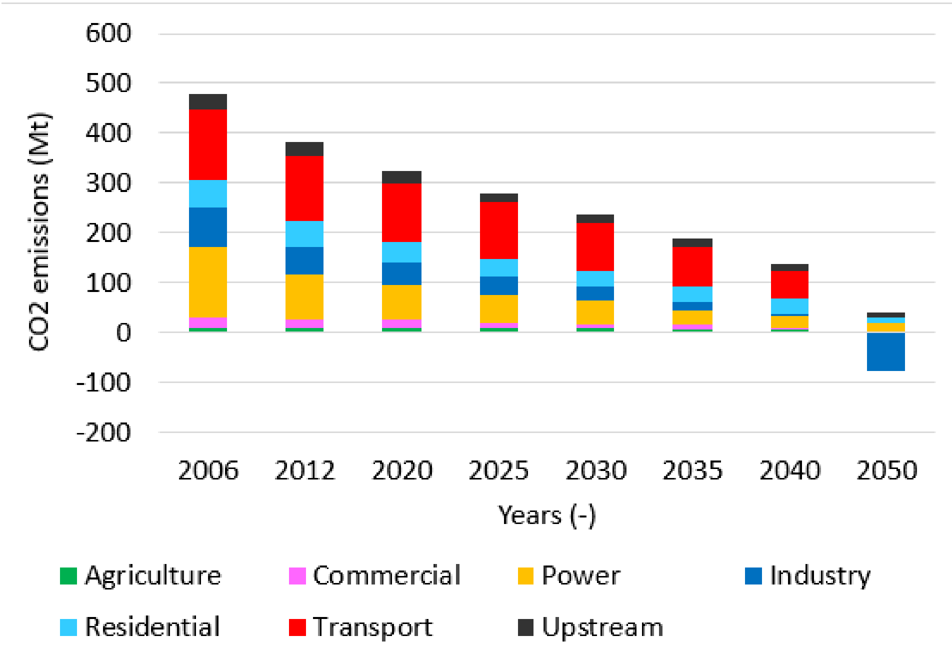

Figure 14: MACC80 scenario: emissions trajectory up to 2050 for the different sectors.

Eventually, in the MACC80 scenario in Figure 14, negative emissions can be achieved by 2050 (-37 Mt), again thanks to the contribution of CCS in the industrial sector. The major reducion in yearly CO2 is achieved in the commercial and transport sector, both getting at zero emissions, while the residential sector achieves -55% emissions reduction.

All in all, Figures 7-14 highlight how the adoption of expensive, low-carbon technologies is generally delayed to the last decade of the analyzed time scale, with the transport and the power sectors always being the most hard-to-abate ones. On the other hand, resorting to CCS in the industrial sector makes it possible to drive the system towards net-zero emissions. However, uncertainties are still there on the possibility to develop cost-effective CCS-equipped plants, even though the very high costs implemented in the model (generally higher than for "traditional" plants) make such technologies anyway regarded as cost-effective in the integrated supply-demand system represented in TEMOA-Italy.

3.1 Marginal abatement cost curve

Putting together all the different, progressive reductions of CO2 in the different scenarios analyzed above, the MACC is finally generated considering the marginal cost for the CO2 emission commodity provided as output from the TIMES model runs. The different points of the MACC represented in 15, each corresponding to a progressively increasing level of emissions reduction according to the indicated scenario, show growing levels of the cost of carbon at each step. While the cost of the CO2 commodity stays well below 500 €/t up to the MACC30 scenario, the largest variations between two adjacent scenarios are even more noticeable at high levels of emissions reduction (from MACC50 on), and the transport sector is mostly responsible for that. This can be noticed from the very strong contribution to incremental emissions reductions in MACC50, MACC60, MACC70 and MACC80 given by the transport sector, leading to a marginal cost of the CO2 emission commodity even higher than 2000 €/t in the MACC80 scenario.

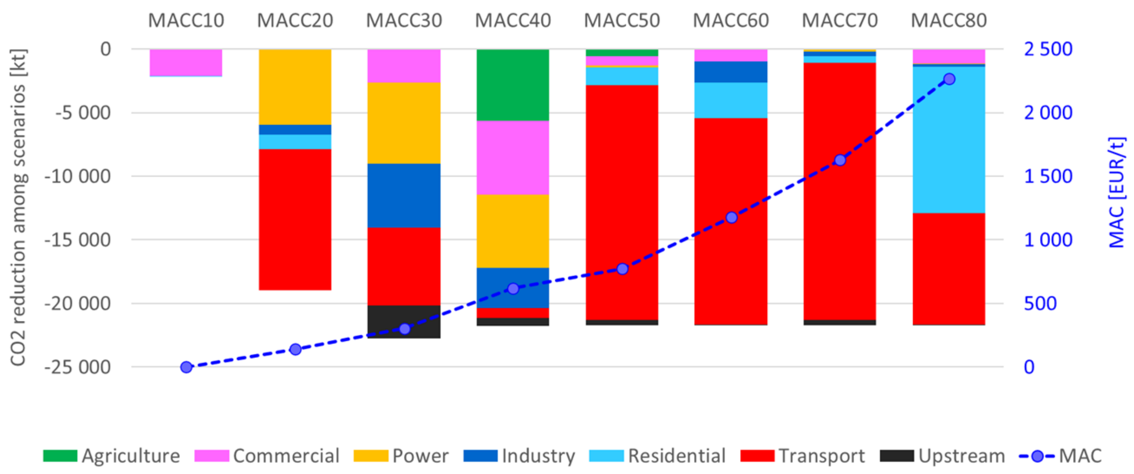

Figure 15: MAC curve for progressive lvevels of emissions reductions in 2050

4 Conclusions

In this work, a model-based MACC evaluation is presented based on the Italian case study. Marginal abatement cost evaluations are usually carried out by consulting firms to drive investment choices on the basis of expert-based analyses and are used to identify high-potential, low-cost technologies and practices focusing on single parts of the energy system or even on small sets of technologies in specific production chains. The use of quantitative modeling tools, and in particular energy system optimization models, can exploit the characterization of the full energy system to allow the overall impact of emissions mitigation measures in a holistic way, i.e. assessing the impact of the entire system instead of adopting a myopic and limited viewpoint.

The analysis carried out in this work is conducted through the energy system optimization model TIMES-Italy, relying on a wide set of technologies covering all the energy supply and demand sectors, and on a time scale up to 2050. 8 scenarios were studied, starting from a baseline scenario with no emissions reduction constraints, then assigning progressive decarbonization targets for the year 2050. The selected emissions reduction levels span from a -10% (MACC10) scenario up to MACC80 (-80%) scenario.

The results of the different scenario runs performed for this analysis show how, starting from a baseline scenario with 35% CO2 emissions reductions in 2050 with respect to 2020, progressively increasing decarbonization can be reached at a very high cost when the emission target is set at the last year of the examined time scale. Indeed, while industry and transport - the so-called "hard-to-abate sectors" - are unsurprisingly the most expensive to be decarbonized, while also providing a wide set of alternatives to achieve the target, the sectoral results obtained in this work show how the adoption of CCS measures in the industry become crucial at high levels of required decarbonization. On the other hand, the decarbonization of the transport sector is decisive at each emission reduction step.

The obtained cost curve depicts a situation where the carbon cost at low levels of emissions reduction with respect to the baseline scenario are much lower than in the case of large reduction levels. In particular, the carbon price computed for the full decarbonization of the Italian energy system is even higher than 2000 €/t in 2050. This value is even more impressive when considering that the current, average carbon tax applied in Italy is set at almost 20 €/t, calling for huge efforts in driving the energy system towards carbon-neutrality and indicating that efforts are better to be undertaken in a progressive way instead of focusing all mitigation measures at later periods in time (as in the case of 2050 in this work).

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