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FEUP FACULDADE DE ENGENHARIA
UNIVERSIDADE DO PORTO

MSc Thesis

The several paths for the self-sufficiency of the Portuguese energy system

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Submitted in fulfillment of the requirements for the degree of Master in Mechanical Engineering by the Faculty of Engineering of the University of Porto

Porto, September 2024

Paths for the self-sufficiency of the Portuguese energy system

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Abstract

Modern society is heavily reliant on the energy system for day-to-day needs, recurring, e.g., to oil products for transportation or electricity in the households. However, the end-users may not be able to make use of this energy carriers if these are not properly produced and transmitted to them. The matter of security in the energy system arises and, for a mostly energy importing country such as Portugal, this security may be at risk with the dependence on foreign resources.

This thesis seeks to explore how the Portuguese energy system can transition from a country with little endogenous energy production to a self-sufficient one. With this in mind, an energy model was developed to represent the system and assess the several paths for self-sufficiency.

The model was built from previous existing ones, performing a full revision on their techno-economic parameters and completing the disaggregation process with the inclusion of end-use technologies for the agricultural sector. From this, several scenarios were built to determine how if the system could evolve to self-sufficiency and what would be the major drivers for that transition.

The findings highlighted that introducing policies such as higher penalties for the emissions of greenhouse gases would not be sufficient to lead the system by itself into energy independence. However, if certain investments were to be made in producing endogenously energy carriers such as electricity and hydrogen, these would bring a positive impact on this process of reaching self-sufficiency. This study also concluded that the reduction on the imports of foreign energy resources would also lead to a cutback on greenhouse gases emissions.

Keywords: self-sufficiency, energy modelling, energy systems, techno-economic review, emissions reduction, *OSeMOSYS*.

Resumo

A sociedade moderna está fortemente dependente do sistema energético para satisfazer as necessidades diárias, recorrendo, por exemplo, a produtos petrolíferos para o transporte ou electricidade para uso doméstico. No entanto, os utilizadores finais poderão não ser capazes de fazer uso destes vetores energéticos se eles não forem devidamente produzidos e forem, de seguida, transmitidos. A questão da segurança no sistema energético surge e, para um país principalmente importador de energia como Portugal, esta segurança pode estar em risco com a dependência de recursos estrangeiros.

Esta tese procura explorar como o sistema energético português pode fazer a transição de um país com pouca produção de energia endógena para um país auto-suficiente. Com isto em mente, foi desenvolvido um modelo energético para representar o sistema e avaliar os vários caminhos para a auto-suficiência.

O modelo foi construído a partir de outros já existentes, realizando uma revisão completa dos seus parâmetros tecno-económicos e completando o processo de desagregação com a inclusão de tecnologias de uso final para o sector agrícola. A partir deste ponto, foram construídos vários cenários para determinar como o sistema poderá evoluir para a auto-suficiência e quais seriam os principais impulsionadores para essa transição.

As conclusões destacaram que a introdução de políticas como penalizações mais elevadas para as emissões de gases com efeito de estufa não seria suficiente para levar o sistema por si só à independência energética. No entanto, se certos investimentos fossem feitos na produção endógena de vetores energéticos como a electricidade e o hidrogénio, traria um impacto positivo neste processo de atingir a auto-suficiência. Este estudo concluiu, também, que a redução das importações de recursos energéticos estrangeiros também levaria a um decréscimo nas emissões de gases com efeito de estufa.

Palavras-chave: auto-suficiência, modelação energética, sistemas energéticos, revisão tecno-económica, redução de emissões, *OSeMOSYS*.

Se mais ninguém teimar, vais ver,
que nunca nada muda.

Tomás Wallenstein

Agradecimentos

Como não vivemos sozinhos e nada se faz inteiramente de uma forma totalmente independente, torna-se necessário fazer os devidos agradecimentos.

À minha orientadora, Prof. Zenaida Mourão, e aos co-orientadores, Tomás Rocha e Adrian Galvez, um especial agradecimento por toda a disponibilidade e prontidão em ajudar que mostraram durante todo o processo da dissertação, mas também pela partilha de conhecimento e pelos conselhos dados, sem os quais este projeto nunca teria atingido o patamar que atingiu.

Aos meus pais, pelo exemplo, por todas as oportunidades que me deram sem nunca esperar algo em troca, pela paciência e por sempre confiarem inteiramente em mim e nas minhas escolhas. Aos meus irmãos que, nos acordos e desacordos, sempre me fizeram desenvolver o meu espírito crítico. Aos meus sobrinhos, por sempre me fazerem perceber o que é verdadeiramente essencial e como posso ser verdadeiramente feliz. Um agradecimento especial à avó João, pelo exemplo de vida e de brio no trabalho, mas também pela dedicação à família.

À Luísa, por sempre mostrar o que há de melhor em mim, pelo apoio nestes e noutros meses e pela motivação que me deu quando esta me faltava. Aos meus amigos e colegas que me acompanharam nestes últimos tempos, pela companhia no trabalho, mas especialmente por me mostrarem que na vida há muito mais do que apenas trabalho.

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Chapter 1

Introduction

1.1 Background and motivation

One of the main concerns of the modern society is global warming and how it is affected by the emission of greenhouse gases. Part of the Paris Agreement's main goals are to keep the global average temperature increase considerably under the threshold of the 2 °C, trying to limit it to 1.5 °C; and to push for the development of low-carbon solutions, defining the second half of the century as the target for having all countries with net zero Greenhouse Gas (GHG) emissions. As a commitment to these objectives, the Portuguese government developed two strategic documents aiming for the decarbonization of the national system by 2050. Developed in accordance with each other, these documents are the *Roteiro para a Neutralidade Carbónica 2050*, or RNC2050 (Roadmap for Carbon Neutrality) [1] and the *Plano Nacional Energia e Clima 2021-2030*, or PNEC2030 (the National Plan for Energy and Climate) [2], and, as the abbreviations indicate, have target-years of, respectively, 2050 and 2030.

One of the dimensions analysed in both these documents is the reliance of the Portuguese energy system on foreign energy resources. Energy imports represented approximately 35% in the national import balance for the year of 2015, having a great impact on the final consumer's energy bill. Recent geopolitical events, such as the war in Ukraine, showed that the dependency on foreign resources, especially the reliance on Russian natural gas, can compromise the security and stability of energy systems. Even though the natural gas represented less than 10% of imports for Portugal, it shows how the lack of stability of other countries from which Portugal imports resources can affect the security of national system.

According to PNEC2030 and RNC2050, endogenously produced renewable energy resources and renewable gases such as hydrogen and biomethane will be the main energy resources used for the substitution of the imported fossil fuels resulting in a decrease of the national dependence on foreign resources, as there is no national exploration of natural gas and oil. This is expected to result in a reduction of the energetic dependence from around 76% in 2015 to below 20% in 2050 [1]. Figure 1.1 shows the national energetic external dependence from 1990 until 2021, showing an overall decrease in this period, but still remaining in values above 60% [2].

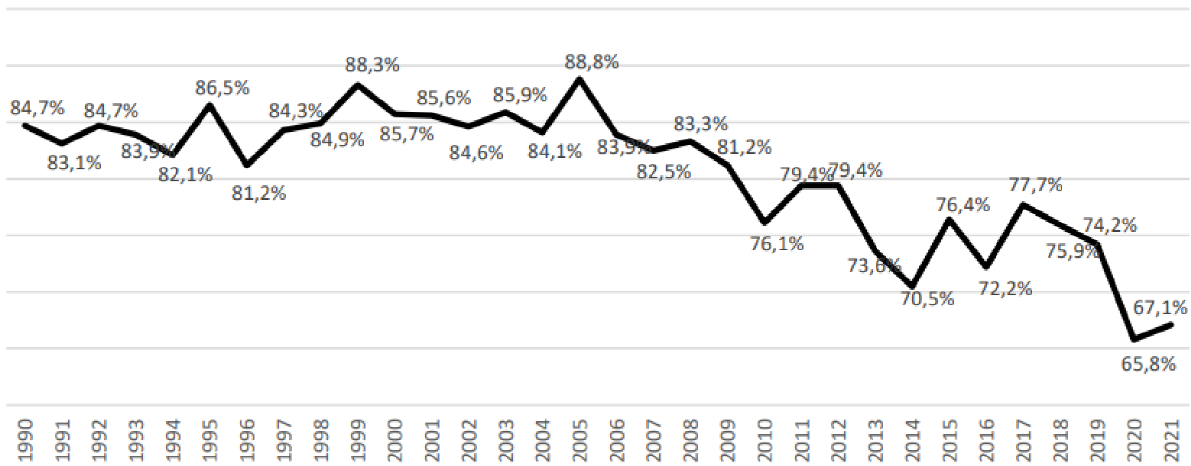

Figure 1.1: External energy dependence evolution in Portugal

The national roadmaps for 2030 and 2050 were developed with the aid of energy models which consist of representations of the full energy system, starting from the energy imports and primary energy production and mapping the energy conversion to the end-use technologies and respective energy services. Several models were developed in the past representing the Portuguese energy system making use of different tools and techno-economic information to generate alternative evolution scenarios of the energy system. Most evaluate the incorporation of high shares of renewable energy sources but, as it will be shown in chapter 2, none set the main goal of self-sufficiency (or very little dependence) of the system. This would not necessarily result from the decarbonization of the system per se, as countries could still rely on imports of bioenergy, e-fuels, hydrogen and green electricity. Thus, the motivation for this thesis is to assess the different paths of evolution of the Portuguese energy system to carbon neutrality, under the constraint of maximizing self-sufficiency, i.e., minimizing the imports of energy resources. The motivation is that these pathways also lead to economic improvements at the macro level from a reduction in the countries imports overall.

1.2 Research questions and objectives

The main objective of this study was to asses the self-sufficiency of the Portuguese energy system under different scenarios of evolution of the energy system to 2050. To achieve this goal, the study addresses the following research questions:

- What are the pathways of evolution of the energy system that simultaneously lead to self-sufficiency and decarbonization of the national energy system?;
- What is the best way to represent the Portuguese energy system, considering all of its elements from imports and centralized production to the end-use sectors?;
- How can this representation help in the assessment of the path for self-sufficiency?.

To address these research questions, the following specific objectives have been defined:

- To carry out a comprehensive literature review on energy system modelling focusing on the analysis of the national energy system, identifying the gaps in previous studies;
- Extend an existing energy model to cover the dissagregation of energy uses to final services for all sectors while carrying out a revision of the techno-economic data of the existing model;
- Develop and analyse various scenarios that identify the necessary measures and policies to achieving self-sufficiency in coordination with the decarbonization targets.

1.3 Outline of the thesis structure

This thesis is organized in the following chapters:

1. Introduction: This chapter provides an overview on the current need for decarbonisation of the energy systems, as well as the state of the Portuguese energy system in the topic of self-sufficiency, explaining its importance. Following this, energy modelling is first approached. Research questions and objectives are also described.

2. Literature review: This chapter gives further context on the Portuguese energy system and conducts a literature review on energy modelling, describing its parameters accompanied by a description and comparison of already developed energy models, focusing on models describing the Portuguese energy system. The major modelling tools are also described and compared.

3. Methodology: This chapter describes the methodology followed in this thesis. Generally providing a description of the process used to build the energy model, the procedure started by identifying a reference energy system model as a starting point, moving on to the full characterization on the parameters and assumptions that were considered when developing the model. This characterization is followed by the portrayal of the disaggregation procedure that led to a complete representation of the end-use sectors. Afterwards, the base year was extensively described, with this being the starting point for all the scenarios that were subsequently described.

4. Results and Discussion: Presenting the findings of the research, this chapter focuses firstly on a broad description of the reference scenario and then establishes a comparison with the other scenarios, focusing on their outcomes in terms of the contribution to energy self-sufficiency.

5. Conclusions and future work: This chapter summarises the main findings of the research, while also discussing the limitations of the developed model. Suggestions for future work are also provided.

Chapter 2

Literature Review

To examine existing research on energy modeling, particularly in the context of the Portuguese energy system, a comprehensive literature research was carried out. This section presents a compilation of various models, categorizing them and emphasizing areas for improvement and further development. The relevant models and literature were identified through searches on ScienceDirect and Scopus using keywords such as 'Portugal', 'decarbonisation', 'pathways', 'energy model', 'techno-economic', 'renewables', and others, as well as literature recommendations from the supervisors. Following the collection of the reference articles, further research was conducted by reviewing citations of these articles.

2.1 Further context

In 2020, total consumption of final energy in Portugal exceeds 600 PJ (as per the DGEG energy balance for 2020, [3]). In terms of primary energy consumption for 2020, oil products dominate, accounting for nearly half of the total consumption. Renewable sources follow with 22%, natural gas with 18% and coal with 14%. In terms of final energy consumption, oil products still represent half of consumption, followed by electricity at 26% and natural gas at 12%. [1] This highlights the significant reliance of the Portuguese system on fossil fuel primary resources, contributing for its external dependence. System emissions reached 56.5 MtCO_2eq in 2021 [2]. As this value does not meet the interim targets outlined in international agreements such as the Fit-for-55, several targets were defined in the roadmaps mentioned previously.

For 2030, the objectives and trajectories are defined in PNEC2030. This action plan was recently revised, leading to a change in the emissions reduction target. Previously defined at 17%, the new emission reduction considering 2005 emissions is of 28.7%. This reduction varies across end-use sectors, with a 70% target for services buildings, 35% for residential buildings, 40% for transports and 11% for agriculture, all based on 2005 emission values for each one of the end-use sectors. The revised PNEC2030 also sets an objective for 49% of final energy consumption from renewables [2]. On the topic of energy security, policies are carried out with the objective of substituting fossil fuel imports by endogenously produced renewable resources, supporting the reduction of energy dependence, as well as the reduction on total energy consumption, through the improvement of the energy transformation technologies' efficiencies.

For 2050, the reference roadmap is RNC2050. While PNEC2030 also sets objectives for 2050, this document provides pathways to reaching carbon neutrality in 2050. With the Paris Agreement outlining a reduction of 90% in emissions relative to 2005, the roadmap stipulates that consumption of primary energy from renewable energy resources must represent a share between 81% and 85% in 2050, which would contribute to a reduction of energy dependence on imports to between 19% and 15%. As for final energy levels, electricity is set to be the main driver of the decarbonisation and is expected to represent a share of two thirds of the total final energy consumption. Despite being referred in a more conservative way, hydrogen is an emerging solution for the partial substitution of fossil fuels, especially endogenously produced green hydrogen [1] .

2.2 Energy system modelling

An energy model represents an energy system at any scale and is primarily used to aid decision-making in planning future energy systems. These models provide insights into how energy technologies can evolve, offering different pathways toward carbon neutrality. They also compare the advantages and disadvantages of various energy sources or technologies [4].

Energy models integrate technological (how energy is transformed), socioeconomic (demand and cost factors), and environmental (e.g., GHG emissions) parameters through mathematical formulations to simulate energy systems. Some models are pre-configured with these parameters, while others require analysts to define them. Though energy models share the goal of representing energy systems, they present differences in key aspects, such as the modelling approach, analytical formulation, spatial scope and scenario selection criteria.

Based on the parameters defined for the literature search, several models were identified and compared in terms of their characteristics to select the most suitable for the objective of this thesis. The following sections describe the categories considered in the comparative analysis of the models, exploring different types of models, their applications, and their relative advantages and disadvantages.

2.2.1 Modelling approach

Energy models are commonly classified as either bottom-up or top-down. Bottom-up models are technology-focused, using detailed descriptions of technologies and their techno-economic parameters to determine which technologies to use based on objectives such as cost or emissions reduction. These models are useful for planning future energy infrastructure in line with specific policies and objectives [5].

In contrast, top-down models begin with macroeconomic parameters, such as energy prices, and define the energy system's demand and supply based on these inputs, as well as on the overall economy evolution. Typically less detailed, these models, often referred to as macroeconomic models, are driven by projections of economic indicators and examine how these relate to the needs of the energy system [6].

2.2.2 Modelling framework

Based on their analytical approach, energy models can be classified into three main categories: optimization, simulation, and accounting models. Each type has distinct characteristics and is used for different purposes in energy system analysis.

Simulation models are used to simulate the behavior of an energy system under specific conditions without actively optimizing for an objective. Rather than searching for the "best" solution, simulation models replicate how the system would function under a predefined configuration of technologies, demand and other parameters. They are used to gain insights into the operation of the system under current or future configurations but do not suggest improvements or optimal configurations. Simulation models are often used to explore the impacts of specific policies, technologies, or demand changes on the existing system without forecasting future changes.

Optimisation models aim to find the "best" solution for a given objective, typically minimizing system costs or maximizing certain outcomes like renewable energy use, taking into account a set of constraints set by the analyst. Many optimization models aim to minimize the Net Present

Value, i.e., of reducing system's costs over a given horizon. Others may prioritize objectives such as reducing greenhouse gas emissions or increasing the share of renewable energy sources.

Accounting models track and report the flow of energy, emissions, and costs throughout a fixed configuration of an energy system without actively optimizing or simulating system behavior. They are mainly used to account for inputs and outputs, such as energy consumption by sector, GHG emissions, or financial expenditures. Accounting models are often combined with optimization models, to enhance their analytical capabilities. These models are particularly useful for creating baseline scenarios, which can then be compared to policy or intervention-driven scenarios.

2.2.3 Spatial Scope

The spatial scope of a model defines the region of analysis: regional, national, or local.

Regional models typically cover more than one country, normally considering the energy system of countries of interest and the interconnection between them. These types of models may consider the region as a whole or several regions independently and the interactions between them. National models are the most common, as energy policy and planning is usually carried out at a national level. Finally, local models are less represented in the literature analysis, and are mostly carried out for large states or regions within countries, with considerable land area and/or population.

2.2.4 Planning horizon and time resolution

The planning horizon and time resolution are two key time-related parameters in energy models. The planning horizon refers to the period over which the model is applied, while the time resolution defines how time is divided within that period.

According to the planning horizon, models can be classified into three categories: short-term, medium-term, and long-term. Short-term models cover 1–5 years and are often less relevant for long-term energy planning.

Medium-term models typically focus on 2030, a key milestone used to assess specific emissions goals and measures towards carbon neutrality in 2050. The most common long-term models usually target 2050 to assess how energy systems can evolve to meet carbon neutrality goals.

Temporal resolution has a considerable impact on both the accuracy of the results of the model and on the computational effort. There are many different approaches on the division of the time-frame, with the reference being how one year of analysis is divided. Each one of the divisions is called a time-slice, i.e., a year is divided in time-slices. The interest in dividing a year in time-slices is to accurately characterize parameters with temporal variability, such as energy demand and the capacity factors for energy resources.

One approach would be to divide one year into 8760 time-slices, with this representing an hourly resolution. However as this would represent a big computational effort in a model representing several years, this resolution is mostly applied in models that only analyse one year. Another frequent division is the four seasons of the year. Following this, the division can also consider day, night and peak times, or even a representation of the hours of each day. Models may also consider day-types, such as week days and weekend days. In order to increase the time resolution of yearly planning models, a division of the year into representative time-slices can should be considered, all this providing greater flexibility in terms of representing the actual energy system.

2.2.5 Energy carriers, technologies and level of disaggregation modelled

In terms of energy carriers and technologies, models can encompass the entire energy system or focus on specific flows and transformation processes, such as the power system or heat production. Most commonly, models focus on primary to final energy resource transformation, including the imports and production of fossil fuels, renewable, or other primary resources.

The level of disaggregation indicates the level of detail of the model in the representation of the transformation of primary energy sources into final or useful energy forms. The model becomes more complex when it includes both a high level of detail on supply-side technologies (transforming primary energy into usable forms) as well as a high level of detail on demand-side technologies (representing end-use energy consumption). Models that disaggregate energy use at the "useful" level require detailed characterization of demand-side technologies and typically mapping of end-use services, while those that stop at the "final" energy level are usually easier to populate, as access to information tends to be more straightforward.

2.2.6 Modelling objective and criteria to select the scenarios

The objectives of energy models often focus on evaluating how policies, evolution of demand, or introduction of new technologies can shape the future energy systems, often in the context of decarbonization.

Typically, energy planning includes developing alternative narratives of evolution of external circumstances that affect energy supply or demand, creating a set of possible future changes for parameters in the models, such as costs of technologies, or levels of demand services. Definition of diverse models allow comparisons between different policy and technology choices. The starting point is usually a BAU, i.e., the Business As Usual, which assumes that socio-economic trends and energy policies do not change within the modeling horizon. These are then compared with scenarios that set certain restriction within the model parameters to reach e.g., carbon neutrality, to meet targets defined in international agreements (Kyoto Protocol, Paris Agreement, Fit For 55, ...), national or international roadmaps.

2.2.7 Model and data accessibility

Availability of open-sourced models are increasingly important, to foster collaboration, improve understanding, and increase model precision and applicability. [7] It also allows for easier customization and adaptation of existing models.

Based on accessibility, models can be grouped into the following categories: open-sourced, open-access, and commercial. The former category is only accessible through licensing and typically requires a fee to access the full version. Fully open-sourced models allow full access to modeling features and access to the code. More commonly, energy modelling tool are open access, which means that although some part of the model is freely available, these models do not offer access to the code or require third party commercial software to run. A widely used model in this last group is the TIMES suite of models.

Access to techno-economic data used to characterize the model is also important for understanding the assumptions and parameters used in the model. It also aids in developing new models for similar energy systems.

2.3 Models developed in literature

Table 2.1, summarizes models from literature, describing them based on parameters discussed earlier. Ref indicates the reference of the model, SS refers to the spatial scope, PH to the planning horizon, TR to the temporal resolution, ECM to the energy carriers modelled, TM to the technologies modelled, LoD to the level of disaggregation, MF&T to the modelling framework(s) and tool(s), OS? to the accessibility of the modelling tool (where OS stands for open sourced, OA for open access and C for commercial), A to the availability of the input data (Yes if this data is available and No if it is not), and YoP to the year of publication of the paper where the model is described, available in the Reference column. The majority of the models focus on national-level analyses with long-term planning horizons, however varying temporal resolutions. For example, hourly resolution is common in models analyzing a single year, while seasonal divisions are more typical for longer timeframes.

Electricity is the most frequently modeled energy carrier, though many models also incorporate the entire energy system. Primary energy resources are consistently represented, and models that include detailed demand-side technologies often achieve a higher level of disaggregation.

Optimization is the dominant modelling framework, sometimes combined with an accounting or simulation one. The more prevalent modelling tools are TIMES (and its variations for various nationaol or regional energy systems) and OSeMOSYS. The majority of the described models consider open access modelling tools, such as TIMES and EnergyPLAN, while the open-sourced ones use OSeMOSYS or similar models. Commercial modelling tools are less represented in the list of models described in the table. Although many models claim to provide data accessibility, this is mostly true for only part of this data. Most times only information for the variation on scenarios is provided.

Table 2.1: Models developed in literature

Ref	SS	PH	TR	ECM	TM	LoD	MF	OS?	A	YoP
[8]	National Portugal	2050	1 h	Whole energy system; All primary resources; All final vectors; H2 production supply	Supply side	Final	Simulation + Optimization (EnergyPLAN + MatLab code)	OA	Yes	2021

Continued on next page

Table 2.1: Models developed in literature (Continued)

[9]	National Portugal	2040	1 h	Electricity only; Only RES-E; All primary resources[1]; Final energy vector; No H2;	Supply side	Final	Simulation (EnergyPLAN)	OA	Yes	2020
[10]	National Portugal	2050	1 h	Electricity and general heat; All primary resources; Final energy vectors for electricity and heat; H2 present but not extensively described;	Supply side	Final	Simulation + Optimization (EnergyPLAN + MatLab code)	OA	Yes	2023
[11]	National Portugal	2050	96 slices (4 daily, 12 months, 2 day-types) yearly	Electricity only; All primary resources[1]; Useful energy vectors; No H2;	Supply and demand side	Useful	Optimization (OSeMosys)	OS	Yes	2018
[12]	National Portugal	2050	288 slices (24 h, 3 day-types, 4 seasons) yearly	Electricity only; All primary resources[1]; Final energy vector; No H2;	Supply side	Final	Optimization (TIMES)	OA	Yes	2014
[13]	Regional Iberian	2030	1 h	Electricity only; All primary resources[1]; Final energy vector; W/ wo/ H2;	Supply side	Final	Simulation (EnergyPLAN)	OA	Yes	2022
[14]	Regional Iberian	2050	288 slices (24 h, 3 day-types, 4 seasons) yearly	Electricity only; All primary resources[1]; Final energy vector; No H2;	Supply	Final	Optimization (PT/SP TIMES)	n.a.	Yes	2014
[15]	Regional European (with 17 different regions)	2050	16 slices (4 ¼ of year, 4 daily time gaps)	Whole energy system; All primary resources; Useful energy vectors; No H2	Supply and demand side	Useful	Optimization (GENeSYS-MOD)	OS	No	2018
[16]	National Portugal	2050	n.a.	Whole energy system;[2] All primary resources; Useful energy vectors;[3] Hydrogen production and supply; [3]	Supply and demand side [3]	Useful	Optimization (TIMES_PT)	OA	No	2021
[17]	National Local (Italy Divided in Regions)	2050	1 h	Whole energy system; All primary resources; Useful energy vectors; No H2;	Supply side	Useful	Optimization (EnergyScope)	OS	No	2022
[18]	National Ireland	2020/50	12 slices (4 seasons; day, night and peak)	Electricity only; All primary resources; Final energy vector; No H2;	Supply side	Final	Optimization (OSeMOSYS)	OS	No	2014
[19]	National Italy	2040	16 slices (4 seasons; 4 day parts)	Electricity only; Few primary resources; Final energy vector; No H2	Supply side	Final	Optimization (OSeMOSYS)	OS	No	2019

Continued on next page

Table 2.1: Models developed in literature (Continued)

[20]	National Portugal	2050	12 slices (day, night, peak hours; 4 seasons)	Whole energy system; All primary resources; Useful energy vectors; Some H2;	Supply and demand side	Useful	Optimization (TIMES_PT)	OA	No	2019
[21]	National Portugal	2050	288 slices (4 seasons, 3 day-types, 24 h) + 1 h	Electricity only; All primary resources; Useful energy vectors; No H2;	Supply and demand side	Useful	Optimization + Simulation (TIMES + EnergyPLAN)	OA	No	2013
[22]	Regional EU28+	2050	12 slices (day, night and peak; 4 seasons)	Electricity only; All primary resources; Final energy vector; No H2;	Supply side	Final	Optimization (JRC-EU-TIMES)	OA	No	2014
[23]	National Portugal	2050	8 slices (4 seasons; day and night)	Whole energy system; All primary resources; Useful energy vectors; H2 production and supply; [4]	Supply and demand side	Useful	Optimization (OSeMOSYS)	OS	Yes	2023
[24]	National Portugal	2050	8 slices (4 seasons; day and night)	Whole energy system; All primary resources; Useful energy vectors; [5] H2 production and supply;	Supply and demand side	Useful	Optimization (OSeMOSYS)	OS	Yes	2022
[25]	National Portugal	2050	8 slices (4 seasons; day and night)	Whole energy system; All primary resources; Useful energy vectors;[6] H2 production and supply;	Supply and demand side	Useful	Optimization (OSeMOSYS)	OS	Yes	2022
[26]	National Equador	2050	1 h	Electricity only; All primary resources; Final energy vector; H2 production and supply;	Supply side	Final	Simulation (EnergyPLAN)	OA	Yes	2024
[27]	National Mexico	2050	n.a.	Whole energy system; All primary resources; Final energy vectors; H2 supply;	Supply side	Final	Simulation (EnergyPLAN)	OA	No	2023
[28]	Local NSW, AUS	2050	16 slices (4 seasons; daytime, night, peak, evening)	Whole energy system; All primary resources; Useful energy vectors; H2 supply	Supply and demand side	Useful	Optimization (Aus-TIMES)	OA	No	2023
[29]	Local Java-Bali	2050	1 h (8760 slices)	Electricity only; All primary resources; Final energy vector; No H2;	Supply side	Final	Optimization (OSeMOSYS)	OS	Yes	2023
[30]	National Norway	2050	48 slices (4 seasons, 12 x 2h gaps)	Whole energy system; All primary resources; Useful energy vectors; No H2;	Supply and demand side	Useful	Optimization (IFE-TIMES-Norway)	OA	No	2023

Continued on next page

Table 2.1: Models developed in literature (Continued)

[31]	Local Matosinhos	2030	1 h	HeatCool only; PV and fossil sources; Final energy vector; No H2;	Supply side	Final	Optimization (energyPRO)	C	No	2018

[1] Taking into account the part of the energy sector modelled.

[2] However, only the analysis on electricity production was performed, so this is relative to the TIMES_PT model.

[3] Relative to the TIMES_PT model.

[4] Extensive description of the Hydrogen supply chain.

[5] Extensive description of the industrial sector.

[6] Extensive description of the buildings sector.

2.4 Existing modelling tools

A comparison between the most commonly used modelling tools is shown in Table 2.2. The main goal in comparing these models, was to identify the most suitable one for use in this thesis work. From the features in the table, EnergyPLAN (Department of Development and Planning, Aalborg University) is a helpful tool for analyzing how a system behaves in a specific year but presents limitations in fully disaggregating the model and optimizing system evolution. On the other hand, OSeMOSYS ([32]) is an open-source and highly flexible modeling tool, allowing the analyst to define all the energy carriers and technologies of interest for any timeframe and temporal resolution. TIMES also allows detailed definition of the whole energy system, but requires access to the proprietary software VEDA (KanORS-EMR, India) to run the optimizations. LEAP (Stockholm Environment Institute), despite being highly flexible, is open access for academic and non-profit use, but not open-source. It is an accounting model, which is not suitable for this project's purposes. It can be coupled with OSeMOSYS to provide additional features. EnergyScope (École Polytechnique Fédérale de Lausanne) combines some characteristics of EnergyPLAN and OSeMOSYS, but it lacks the multi-period investment planning and similarly to EnergyPLAN, is mostly dissagregated only for supply technologies. Lastly, energyPRO (EMD International A/S, Denmark) is a commercial tool with similar characteristics to EnergyPLAN. Given this analysis, OSeMOSYS is the most suitable modelling tool for the objective of this thesis, as it allows flexible, full energy system description and open-access, and fits the time horizon of 2050.

Table 2.2: Existing modelling tools

Model	Time-frame	Temporal Resolution	Technologies modelled	Whole energy system	Open-sourced?	Multi-period investment planning	Sector disaggregation	Bottom-up or top-down
EnergyPLAN	1 year	1 h	Supply	No	No, *OA*[b]	No	No	Bottom-up
OSeMOSYS	*Flex.*[d]	Flex.	Flex.	Flex.	Yes	Yes	Flex.	Bottom-up
TIMES[a]	Flex.	Flex	Supply and demand	Yes	Yes	Yes	Yes	Bottom-up
LEAP	Flex.	Flex.	Flex.	Flex.	No, *C*[c]	No	No	Bottom-up
EnergyScope	1 year	1 h	Flex.	Flex.	Yes	No	Yes	Bottom-up
energyPRO	1 year	1 h	Supply	No	No, C	No	No	Bottom-up

[a] TIMES model has several versions for various countries, each model having variations of the techno-economic parameters according to the energy system of that country and its demand.

[b] Open-access, the model/code can be used free-of-charge but does not have open-sourced capabilities.

[c] Commercial, the model/code cannot be used free-of-charge.

[d] Flexible, defined by the analyst.

2.5 The Portuguese case: models already developed

From all the models mentioned in table 2.1, only some represent the Portuguese energy system. They will be further explored in this section, in order to compare them and evaluate what useful information can be used in the future modelling for this study, and what is lacking and would be important to be considered.

In [8], an optimisation model was developed using EnergyPLAN and MatLab. As EnergyPLAN was used, the model only evaluated one year (excluding the validation of the model for the reference year), which was 2050, all this with a temporal resolution of one hour. The model considers the whole energy system, although only going deeper on the electricity system. The energy carriers only reach the final level, as the model does not model technologies on the demand side. The technologies on the supply side are considered to be fully represented and so all primary resources are taken into account in this model. There is also the presence of hydrogen production and supply on the model. The objective for the development of the models was to perform an optimisation of a system with a great presence of hydropower. For this, three scenarios were considered: a wet year, a dry year and an average year. Some input data regarding demand and installed capacities is available.

In [9], EnergyPLAN was used to simulate a possible future energy system obtaining the maximum energy from renewable sources. The model only considers only the power system and the energy carrier (electricity) is modelled until the final level of energy, obtaining a final electricity energy vector. The technologies are again only developed on the supply side, with all renewable sources being modelled and also the usage of natural gas and imports. Hydrogen is not considered in the analysis, which is performed to the year 2040. The objective of the modelling was to present technical solutions to reduce CO_2 emissions following the Portuguese government's guidelines and a high share of renewable energy supply. Several scenarios were developed, starting with a base scenario, and evolving to BAU and favourable ones for wind and solar energy, ending with a high demand one. Input data is also available for demand and installed capacities.

In [10], an evolution of the previous model is developed also in EnergyPLAN, but this time with the planning horizon of 2050. The model presented several additions in the modelled energy carriers, such as heat and hydrogen (although not being extensively described), and an optimisation process using MatLab. This time, the objective was to present solutions for carbon neutrality in the energy sector, following the same guidelines with a presence of green hydrogen, especially in the transport and industrial sectors. The scenarios include also a base scenario, moving on to pro-solar and pro-offshore ones, one considering the interconnection with Spain and finally a high demand scenario.

In [11], an optimisation model using OSeMOSYS was developed for the target year of 2050. The goal of the modelling was to assess how demand-response would impact the electricity system in the long-term. For that, a model that included all primary resources, technologies for the supply and demand side, and with a useful level of the energy carriers was developed. Hydrogen production and supply was not included in the analysis. The model accounted for 96 annually time-slices, representing 4 daily time divisions of two day-types, all this for the 12 months of the year. The scenarios include a BAU one, one with the objective of reaching carbon-neutrality and one where there are no heavy carbon emission restrictions. Input data is also available for techno-economic parameters for the reference year, for the demand and for installed capacities.

In [31], a local model was developed for the municipality of Matosinhos in the energyPRO software. The model represents the heat production, distribution, and consumption in buildings of the area. Technologies are represented for the supply side, considering fossil and solar energy sources, resulting in a final heat vector, for which the demand is also represented.

No hydrogen is considered in the model. The planning horizon is 2030 and temporal resolution is of one hour. The objective of the modelling was to assess how sustainable would heat and cold supply solutions be in terms of cost-effectiveness under typical conditions for Southern Europe, using Matosinhos as an example. Two scenarios analysed systems without district heating networks excluding and including capital costs, one analysed the replacement of natural gas boilers with heat pumps maintaining compression chillers, another one added to the last photovoltaic systems to feed the heat pumps and compression chillers, and a last one analysed an inclusion of a district heating and cooling network. Input data for demand and techno-economic parameters is available.

Another way to represent the Portuguese energy system is integrating it in a bigger system which also includes Spain, i.e., a model for the Iberian peninsula. That is the case of [13], where the objective was to perform a simulation followed by an analysis of the power systems of both Portugal and Spain based on the goals described in the national energy and climate plans for 2030. For this, a model was created for Portugal, another for Spain, and then one that integrated both of them. With the technologies defined only on the supply side, but fully represented, all the primary energy resources are considered. As there are none on the demand side, the final level of energy carriers is a final electricity vector. For the Portuguese model, two scenarios were applied: one following PNEC 2030 guidelines, and one where the guidelines from EN-H_2 were added to the PNEC 2030 one. This last scenario accounts for the presence of hydrogen in the energy system. As this model was developed in EnergyPLAN, the temporal resolution is of one hour. There is no information on input data for this model.

In a[14], a model for the Iberian peninsula was also used, considering a TIMES model for Portugal, Spain and their interconnection: the PT/SP TIMES. With the highest time resolution in the papers that were analysed for this work, it divides the year in 288 time-slices, accounting for the 24 hours of 3 day-types, for each of the 4 seasons, with the planning horizon of 2050. However it only disaggregated the energy system to the level of final energy. The primary resources are all explicitely modelled, although the model does not consider hydrogen. The goal was to analyse the possibility of full decarbonisation of the Portuguese power system in 2050. A secondary objective was to determine the importance of the interconnection with Spain, considering two scenarios. A first where Portugal is considered as an isolated system, and a second where the import/export balances of electricity are considered for the Iberian power systems.

The base TIMES model was used for the Portuguese system in [12] and [21]. The TIMES model was specifically developed to represent the Portuguese energy system, the TIMES_PT model, and has been extensively used to model future transitions on the Portuguese energy system [16], [20], [33]. This model benefits from having an extensive database for recent and future technologies and energy carriers of the energy system, although without updates for at least five years. The objective of this model is to satisfy the demand for the least possible cost. Another important reference inside the TIMES models is the JRC-EU-TIMES [34], used, e.g., in[22], which models the systems of the EU 28 countries and of Switzerland, Norway and Iceland. As each region represents one country, with the input data for the model being publicly available, it arises as a helpful basis for the configuration of other models.

On previous MSc theses, a model using the OSeMOSYS tool was developed. This model described the whole chain of energy carriers (including end-use technologies), with the inclusion of the production and supply of hydrogen. In [24], the industrial sector was disaggregated, while in [25] the same was applied but to the buildings sector (residential and services). In [23], the transport sector is also disaggregated, but most importantly the supply-chain for hydrogen was extensively described and included. This latter thesis expands on the models with the detailed description of the industrial and buildings sectors.

2.6 Conclusions

From the analysis of the state of the art on energy modelling and specifically on representations of the Portuguese energy system, it is concluded that not only there is no model developed that analyses the self-sufficiency of the Portuguese energy system, but also there is no open-sourced, fully disaggregated model with the input data being completely available.

As these were the objectives established for this thesis, and after confirming this would be a novelty, the following steps for the development of the model were taken. This includes the development of a diagram to represent the system that will be modelled, including all the technologies and energy vectors. After that, it is needed to identify the sources for the necessary data that will serve as the input of the model.

Chapter 3

Methodology

With the objective of assessing the paths for the Portuguese energy system's self-sufficiency, a bottom-up approach was carried out with an optimisation framework. On the spatial scope, it is included in the national models' group. The planning horizon is set to 2050, thus being a long-term one, dividing each of the years of analysis in 8 representative time-slices that represent day and night for each season. The model will represent the system as a whole, from the primary resources' level to the useful energy one for several disaggregated sectors, with all the main energy carriers represented in between, including hydrogen.

3.1 Reference Energy System

The base for the development of the model was the Reference Energy System model (REF), shown in 3.1. This baseline energy system was developed as previous work by the research group and is implemented in the OSeMOSYS modelling tool. The diagram uses boxes to represent technologies and vertical lines to represent energy carriers. It is read from left to right and models the energy system from primary sources (left) to a final energy level of end-use sectors (right), namely industry, residential and service buildings, and the agriculture and transports sectors. On the primary energy side, it represents imports, collection and mining of the resources, followed by transformation of the primary and secondary energy vectors and their transmission and distribution to final energy level. For each of the technologies depicted, the reference model presented detailed information on costs, operational lifetimes, residual capacities, efficiencies and emissions factors. These techno-economic parameters were mainly gathered from the International Energy Agency (IEA) database. The model considers the starting of the analysis horizon in the year of 2015, ending in 2050.

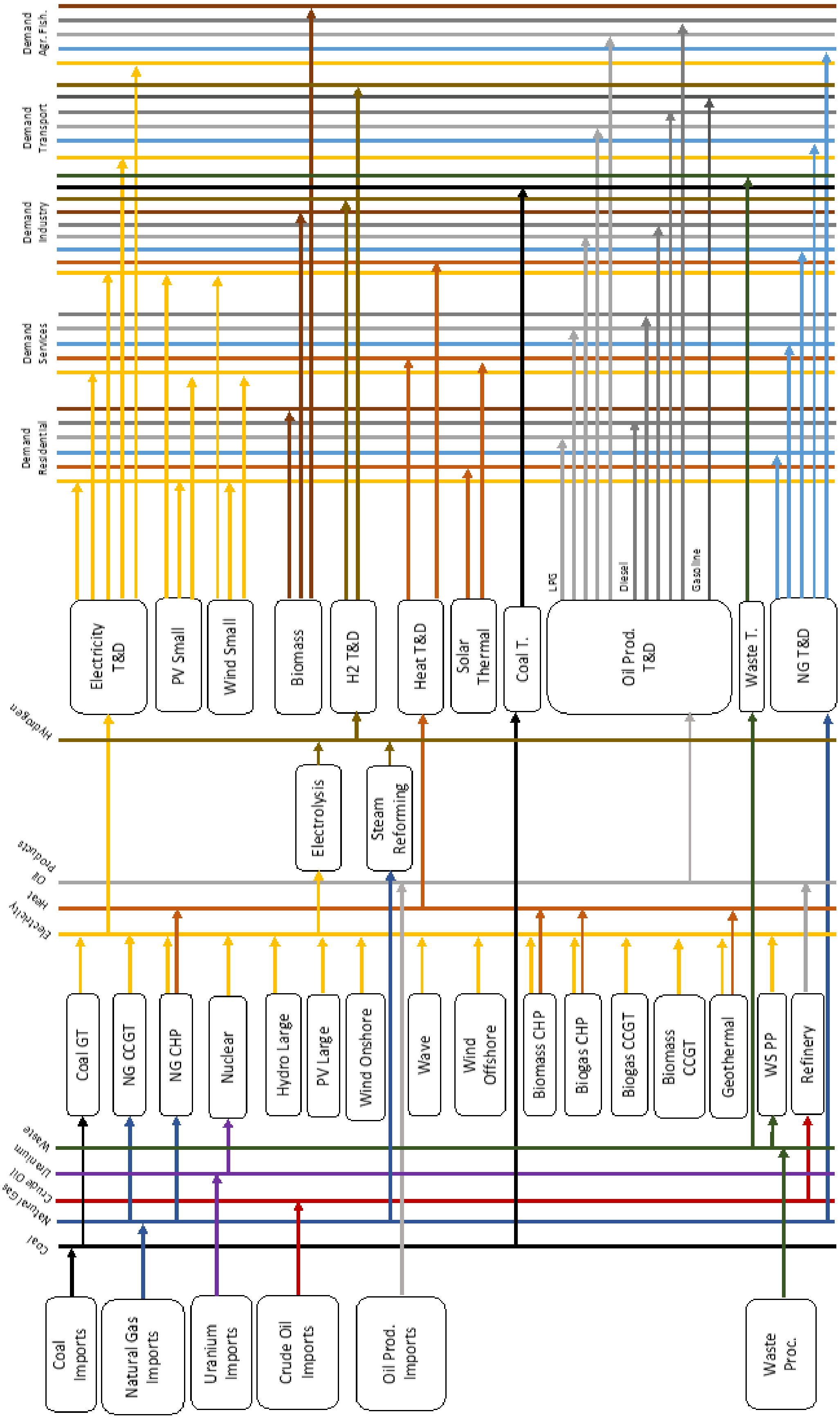

Figure 3.1: Reference Energy System (REF) for the Portuguese Energy System

Despite already describing extensively the primary side of the system, future technologies, which might be introduced in the energy system in the future, were lacking. These will be needed to be incorporated along with technologies and demands on the end-user side, in order to better characterize the needs on this side and allow for an analysis that considers reaching diverse goals such as the self-sufficiency of the system or the fulfillment of emission reduction goals.

From this point, the first step when starting to build an energy model is to define what is going to be characterized, i.e., the level of disaggregation and the energy carriers and tehcnologies to be defined. As seen in the previous chapter, practically all models include the imports and primary production of energy. The model developed in this project also represents this part of the energy sector, including primary resources and energy imports and collection, such as natural gas and coal imports or the collection of biomass and waste. After this, it is also represented the primary and secondary transformations and renewable energy production, including technologies from natural gas cogeneration plants to several centralized hydrogen producers and photovoltaic or wind power plants. This defines what will be titled the primary sector, which provides the following technologies of the model with its necessary carriers.

Following the primary sector, there are two levels which were titled transmission and distribution levels, which represent the transmission of the energy carriers from the primary sector to the end-use ones and offers flexibility to the model. This happens due to the fact that energy demand can be defined on a final level, both generally for the whole energy system (for example, one can define the demand for electricity or diesel for the whole energy system) or for each sector, for example defining the demand for electricity in the residential sector or the demand for LPG in the agriculture sector. This allows the analyst to consider only the primary side of the system, if it better fits the needs of the study, or even for its calibration.

These last levels connect to the end-use sectors, which in accordance with the REF and other previously developed models, were defined to be the industrial, residential buildings, services buildings, transports and agriculture sectors. Further definition on these sectors will be provided in a following section.

A diagram representing the energy model can be found on appendix A. Similarly to the REF, the boxes represent the technologies of imports, production and conversion of resources and energy that are included in the model. The vertical lines represent the energy carriers. The description for the codes used to name technologies can be found in appendix B and the description for the carriers can be found in appendix C.

3.1.1 Implementation of the energy system in OSeMOSYS

For the population on OSeMOSYS, several parameters have to be defined. Their accurate definition has a crucial influence on how the model represents the actual energy system and on how it will behave in the choice of future technologies. The main parameters definitions and assumptions are further explained in this section. The input data that was used to generate the model using OSeMOSYS is accessible in the repository mentioned in appendix D.

Model sets are the parameters that define the general structure of the model. Starting with the region, the analyst has to define one or more regions of interest. This is useful when modelling systems that have real divisions in itself like models that analyze the European Union or the Iberian Peninsula, dividing it in countries or groups of countries. For this case, as the analysis is on the Portuguese energy system, only one region is defined and it is titled Portugal. Following the region, it is important to define the planning horizon of the model in line with the objectives of the study. As the REF, the model was defined to have 2015 as the base year and to end the analysis in 2050.

To better account for variability of both resources and demand, the years are divided in time-slices. This is accomplished by defining representative seasons, daily time brackets and day types in which the year can be divided. In this case, only the seasons and daily time brackets were specified. The year was, then, divided in 4 seasons (representing autumn, spring, summer and winter) and 2 daily time brackets (day and night). Further resolution could be achieved by increasing any of the three parameters, but in order to reach a compromise between resolution and computational effort, it was decided to use this divisions. From this parameters comes the definition of the time-slices, i.e., the names that will be given to the divisions of each year resulting from the previous three parameters. In this case, the time-slices are a combination of the 4 seasons and day and night. A proportion value is attributed to each one of the time-slices, in representation of their share of the year. In this model each night time-slice represent one third of a quarter of the year and the day time-slices represent the other two thirds. Numerically, each one of the night time-slices have a weight of 0.0833 and each day time-slice has a weight of 0.1667.

Two other model sets are the fuels and technologies. Fuels represent the energy carriers present on the model that are a result of the production of technologies. These sets consist on a list of the denominations of each one of the technologies and energy carriers. As it was aforementioned, a list for the technologies and another for the fuels present on the model are in appendix B and appendix C, respectively. The fuels are used to define the demand, which represent the needs of the energy system's users. The model in analysis was built in order to define demand with flexibility, starting by defining it in a final energy level (either for the whole energy system or for carriers specific to each end-use sector) and proceeding to substitute this one with specific end-use demands, such as the demand for space heating in the residential sector, or the demand for car road transportation in the transports sector. In OSeMOSYS, the demand is always defined on an annual basis. However, to account for variability and peak demands, it is possible to identify the demands that do not have a uniform distribution throughout the year. For example, in this model the demand for space heating in the services buildings sector is defined to have a distribution of 25% for winter and autumn days and nights, identified as the time-slices where there would be a demand for space heating, equally distributing the total demand between them. This contributes to the accuracy of the model. Technologies are then defined through various parameters, such as costs (divided in capital, fixed O&M and variable O&M), expected lifetime, residual capacity (associated with a conversion between the units of capacity and the units of activity/production), efficiency (through outputs and inputs ratio, that ratio of which will be the efficiency), maximum/minimum activity (an auxiliary to direct the model to prioritise the use of residual capacity), capacity factor, availability factor and maximum/minimum capacity (mainly to set the limits on the installation of the technology). Further details on the definition of these parameters will be provided in the following section.

Another aspect that needs to be set in OSeMOSYS is the number of modes of operation for technologies. This is useful when there are technologies that can produce several outputs, such as heat pumps that can extract or insert heat in a space. In this model, the number of modes of operation was set to 2 as the technologies defined only have 1 or 2 products from activity, such as in the case of the heat pumps.

Lastly, the model has to contain, if applicable to the analysis, a definition of the emissions that are going to be considered. For the present model, an analysis will be performed to the emissions of greenhouse gases (here represented by equivalent CO_2) and of nitrous oxides (NO_x). From this point, emission ratios can be defined for technologies, which in this model will be majorly associated with the imports technologies, thus defining a general emission ratio for the use of a certain resource. Introducing emissions on the model will allow for the definition of emissions penalties (a cost for the production certain emissions) and emission limits, defined in an annual basis.

Despite not having to be defined in the model itself, it is important to delineate the units that will be used when setting the rest of the parameters. Four different units, represented in Table 3.1, are needed representing costs, capacity, activity/demand and emissions. Note on the exceptions on the capacity for the centralized and end-uses technologies, and for the activity in the transports sector.

Table 3.1: Units used in the model

Costs	**Emissions**	**Capacity**	**Activity**
M€	Mt	Centralized: GW	Transports: Gpkm/Gtkm
		End-uses sectors: PJ/y	All others: PJ

3.2 Disaggregation procedure

As mentioned previously, the model was built considering end-use sectors. These are the industrial, residential buildings, services buildings, transports and agriculture sectors. With these being identified as the more energy intensive sectors, this disaggregation enhances the model's representativeness of the real energy system and its users needs. Adding to the end-use sectors, a full revision of the representation of the primary sector in previous models was carried out. In the following sections, the process of this revision and inclusion for the sectors is explained. In previous MSc theses, models were developed with the full disaggregation for the residential and services buildings [25], for the industrial sector [24] and for the transports sector, but focusing primarily on the full description of the hydrogen value chain and the inclusion of hydrogen fuelled technologies in the end-use sectors [23]. Along with the Joint Research Centre's European Union TIMES (JRC-EU-TIMES) [34] model and the Joint Research Centre's Integrated Database of the European Energy System (JRC-IDEES)

[35], these were the main sources for the population of the model.

3.2.1 Primary sector and Transmision and Distribution

The primary sector is responsible for the transformation of the primary resources, turning them into forms of energy more convenient to the end-use sectors, for example turning natural gas into electricity and heat or crude oil into oil products of interest, or even produce electricity from renewable energy sources.

As it is represented in the energy system diagram in figure 3.1, three distinct levels are present in the primary sector. The first one represents imports and centralized collection of waste and biomass. Following, is the primary transformation level, where important energy carriers such as electricity, heat or oil products are centrally produced. The third level is the secondary transformation one, which primarily includes hydrogen production technologies, some of which utilize products from primary transformation.

For this sector, a full revision was carried out for the costs, efficiencies, capacity factors, operational lifetimes and residual capacities of the REF and of models developed in previous MSc theses [25],[24],[23], as well as the inclusion of diverse technologies such as power plants with carbon capture utilisation and storage and concentrated solar power plants, which were not present in the reference model. This addition and revision was performed resorting to several reports from energy agencies and labs which included techno-economic information, as long as a prediction for their evolution. These reports are namely the National Renewable Energy Laboratory's Annual Technology Baseline [36], the IEA's World Energy Outlook [37], the United States Energy Information Association's Annual Energy Outlook [38] and the International Renewable Energy Agency's Power Generation Costs report [39]. From this reports, the model's primary sector was populated and the parameters that were still lacking were taken from the JRC-EU-TIMES [34] model, always comparing to the parameters that were set in the REF. Despite not being present in this sector, decentralized technologies were also defined. Those are decentralized wind and solar power generators —which are present in the industrial, residential buildings and services buildings sectors —and decentralized biomass collection technologies, which are present in the same three sectors adding to the agriculture one.

For imports and centralized collection technologies, only a variable cost was defined. This represents the unit cost of each specific primary resource. Adding to this, and as it was stated before, the emission are accounted through these technologies by defining an emission ratio for each specific primary resource. Carbon capture utilisation and storage technologies also have an emission ratio, but it is negative and represents 95 % of emissions capture.

After producing the necessary energy carriers, the system needs to route them to the end-use sectors. This is achieved through the transmission and distribution technologies. The costs of transmitting this carriers are contemplated through fixed and variable costs, which means that the model will associate costs of having the capacity of transmitting the carriers and also costs that depend on the amount of energy that is transmitted.

3.2.2 Residential and services buildings sectors

The disaggregation of the residential and services buildings sectors aims for representing the more energy intensive needs of the energy system's users when referring to these buildings. The two are condensed in one section due to the fact that the methodology followed was the same for both of them. This process started by analyzing the main energy demands for each of the sectors, defined on a previously developed model [25]. For the residential buildings sector, these demands comprise space cooling, clothes washing, cooking, water heating, dishwashing, small electrical appliances, space heating, lighting and refrigeration. For the services buildings sector, the demands encompass space heating, water heating, space cooling, cooking, lighting, refrigeration, freezing, clothes washing and small electrical appliances. The values for the demands were collected from the JRC-IDEES database ([35] from the base year until 2021. From this year, the evolution of the demand was considered the same as the model developed in Ivo Cardoso's master's thesis [23].

The choice of the technologies to model is based on the demands and the characterization of final energy vectors used to fuel them, as well as information on actual end-use technologies for these sectors. For this model it followed the same choice of technologies as in Ivo Cardoso's master's thesis, which was based on the JRC-EU-TIMES model [34], João Madeira's master's thesis [25] and Ana Neves' PhD dissertation [40]. For the techno-economic parameters such as costs, lifetimes and efficiencies the assumptions were the same. However, adjustments had to be carried out on the residual capacities when several simulations of the model presented errors, with productions that surpassed the demands and also installing and using new technology capacity in the base year. In order to correct these inconsistencies, calculations were performed based on the demand, the share of residual capacity of each technology in Ivo Cardoso's master's thesis model (relative to each demand), following the same evolution as in this model. As most of the demands are not equally distributed throughout the yearly time-slices, the residual capacity was calculated assuring that the peaks of each demand can be fulfilled by the residual capacity in the base year. The formula for calculating the residual capacities is present in the following equation 3.1.

$$\text{ResCap} = \frac{\text{AnnualDemand} \times \%\text{RC} \times \max\left(\frac{\text{Profile}}{\text{YearSplit}}\right)}{\text{Efficiency}} \tag{3.1}$$

ResCap indicates the corrected residual capacity to introduce in the model, Annual Demand represents the total annual demand applicable to the technology of interest, %RC indicates the share of the residual capacity of the technology considering all the technologies that are able to provide that demand and their residual capacities on Ivo Cardoso's master's thesis model, Profile is the share of total demand for each time-slice, YearSplit is described by the share of the year for each time-slice and Efficiency is, as the designation indicates, the efficiency of the technology for which the residual capacity is being calculated.

Other three parameters had to be defined due to the model occasionally not prioritising the use of the residual capacity. The first is the previously described minimum activity which will force the model to use the residual capacity and thus be more accurate. This minimum activity is calculated by multiplying the demand that the technology is able to fulfill by the share of residual capacity that the technology represents. Despite presenting more accurate results, and related to the definition of modes of operation, a very low variable cost is set for the modes of operation applicable to the technologies, and a very high variable cost is set for fictitious modes of operation that the code generated by itself, with this being the second parameter. The last one relates to maximum activity. The maximum capacity ensures that a proper use is given to the residual capacity and that new installed technologies will not produce in excess surpassing the actual demand for their outcomes. The maximum activity level for biomass utilization was also established in accordance with its consumption trends outlined in the RNC [1], in order to address the model's excessive reliance on biomass during simulations. This adjustment ensures a more realistic representation of the country's biomass production capacity.

3.2.3 Industrial sector

The industrial sector is a very complex one when addressing energy intensive demands, as they are many and so are their respective sub-sectors. As it was identified in Gonçalo Oliveira's master's thesis [24], the energy intensive sub-sectors are the iron and steel, food and beverages, chemical, cement and lime, ceramic and glass, non-ferrous metals and pulp and paper industries. In Table 3.2 there is a representation of the specific demands for each sector.

Table 3.2: Specific industries demands

Iron and steel industry	Crude steel production
	Iron and steel production
Food and beverages industry	Oven heat production
Chemical industry	Amonia production
	Chlorine production
Cement and lime industry	Clinker production
	Cement production
	Lime production
	Kiln heat production
Ceramic and glass industry	Flat glass production
	Hollow glass production
Non-ferrous metals industry	Aluminium production
	Crude aluminium production
Pulp and paper industry	High quality paper production
	Low quality paper production
	Pulp production

Apart from the specific demands on the table, there are others general to the industries. These include HVAC, process heat from boilers, process heat from kilns (not including the one on the cement and lime industry), lighting, machine drive, refrigeration, on site transportation and steam production. Adding to these two demands are considered relative to other and non specific uses, with them being one for thermal uses and another for electricity uses. The condensation of general demands was carried out as in [23].

For this sector, the selection of technologies and their techno-economic parameters also follows the same approach as the one in Ivo Cardoso's MSc thesis. The same corrections as the ones in the previous section was carried out. Residual capacity was defined assuring peak demands, and the minimum activities and variable costs were also defined. In this sector there was no need for the characterization of a maximum activity as the errors stated previously were not happening in this sector.

3.2.4 Transports sector

The transports sector is one of the sectors with the greatest emissions share, with it being nearly 25% [1]. This is due to its high demand for energy and to it being mainly fuelled by oil products. For this model and in similarity with the industrial sector, the demands, technologies and their techno-economic parameters were set based on the model developed in Ivo Cardoso's master's thesis [23]. For the demand and technologies definition, two sub-sectors were considered, with them being the passenger transport and the freight transport. Passenger transport demand is then divided in road transportation by car, by bus, by two wheel vehicles and by metro, rail transportation and aviation transportation. Freight transport is divided in ship transportation, rail transportation, aviation transportation and road transportation by light and heavy duty vehicles. The profile of the demands is uniform throughout the time-slices. In this sector specifically, the demands have other units, with them being in Gpkm for passenger transport and Gtkm in freight transport.

In this sector, the correction of the residual capacities had a simplification, due to the fact that demand is constant throughout the year. Only specific technologies needed adjustments to match residual capacity with the demand, and then the minimum activity was set for all technologies. Variable costs were defined as in the residential and services buildings sectors.

3.2.5 Agriculture sector

The agriculture sector, despite being one of the least consuming sectors, is the one that brings special novelty to the model developed in this work. With this being the only sector that was not disaggregated in previous models, its complete definition fully completes the disaggregation procedure. For this, the first step was to define what would be the carriers considered for the demands. By consulting the JRC-EU-TIMES model [34] in articulation with the JRC-IDEES database [35], the demands were defined as being irrigation, heating, lighting, machinery, ventilation and small electrical appliances. The values for this demands were considered as equal to what was in the database, and then would follow an evolution similar to the demands in the industrial sector.

From this point, the next step was to define the technologies of interest, with them being decided also by making use of the JRC-EU-TIMES model and the JRC-IDEES database. When assessing the techno-economic parameters for the technologies, it was determined that, as the technologies were very similar to the ones in other sectors, namely the industrial and services buildings sectors, these parameters would be equal to the ones in these other sectors. Residual capacity was defined taking into account to what energy carriers were used as fuels in the base year, an information that is available on the JRC-IDEES database. The evolution of the residual capacity also follows a similar path as the ones in the industrial sector. The final step was to set the minimum activity and the variable costs as in the previous sectors.

3.3 Characterization of the base year

The base year is the starting point of the model therefore it has to be accurate for a correct evolution in the optimization process. To better understand this starting point, a description of the base year will be provided in the following sections.

3.3.1 Demand

In figure 3.2, the demand distribution for each end-use sector is represented. Industry has the highest share with 35%, and following are transports with 25%, residential buildings with 21%, services buildings with 17% and the rest is attributed to agriculture. A further approach on each sector's demands will be carried out in the following paragraphs.

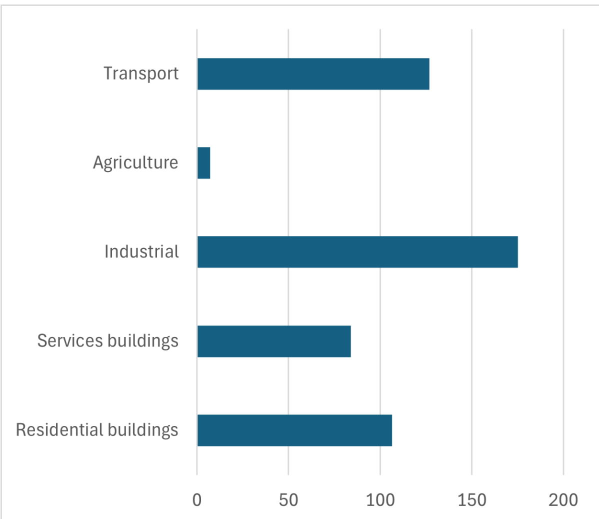

Figure 3.2: End-use sectors' share of total useful energy demand (PJ)

In figure 3.3 the demand distribution for the residential buildings sector is depicted. With a total of 106.4 PJ of demand note that only four of them represent 83% of the total sector's demand. These are, from the highest to the lowest, space heating with 35%, cooking with 20%, water heating with 15% and small electrical appliances with 13%.

The total demand in the services buildings sector is 83.9 PJ and its distribution is represented in figure 3.4. In similarity with the previous sector, space heating has the highest share in total demand (31%), followed by lighting with 19%, cooking with 13% and water heating with 11%.

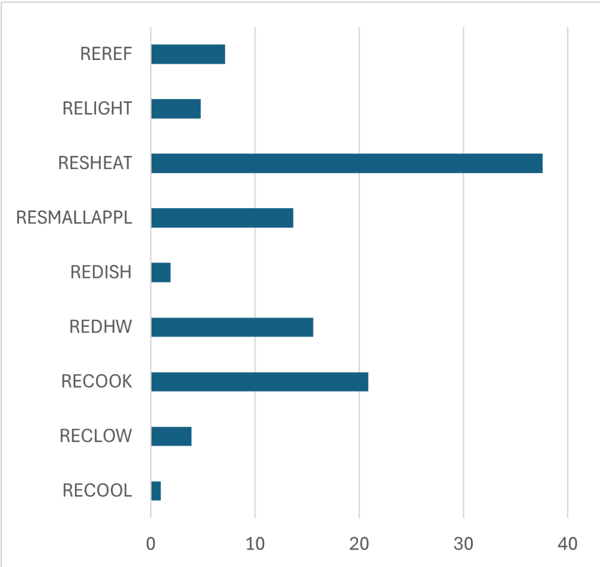

Figure 3.3: Residential buildings sector's useful energy demand distribution (PJ)

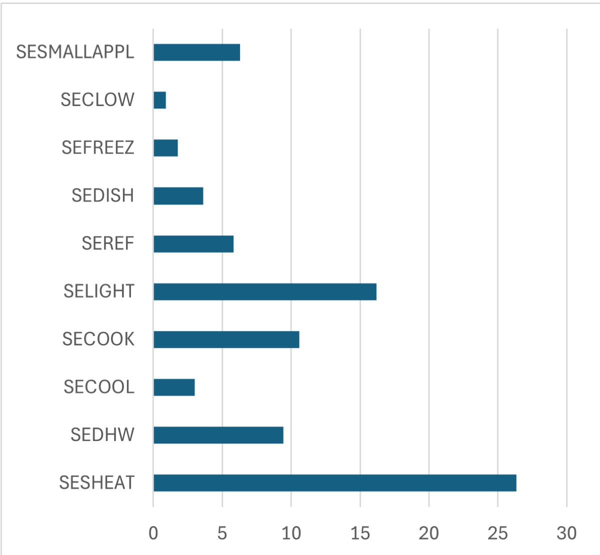

Figure 3.4: Services buildings sector's useful energy demand distribution (PJ)

The industry sector, as the greatest energy consumer, has a total demand of 175.2 PJ. Its distribution is quite complex throughout the several sub-sector specific demands. In order to ease the analysis in figure 3.5 the share of each energy demand is represented, but with the key point that the specific demands are condensed, showing that they represent 50% of the total demand, with other demands such as machine drive and process heat contributing with 14% and 12% respectively.

Representing a quarter of the total energy demand, the transports sector's demand consists of 126.8 PJ. Figure 3.6 shows how it is distributed. With a share adding up to two thirds, the demand for car passenger transport is by far the largest one, with the other third scattered among the remaining.

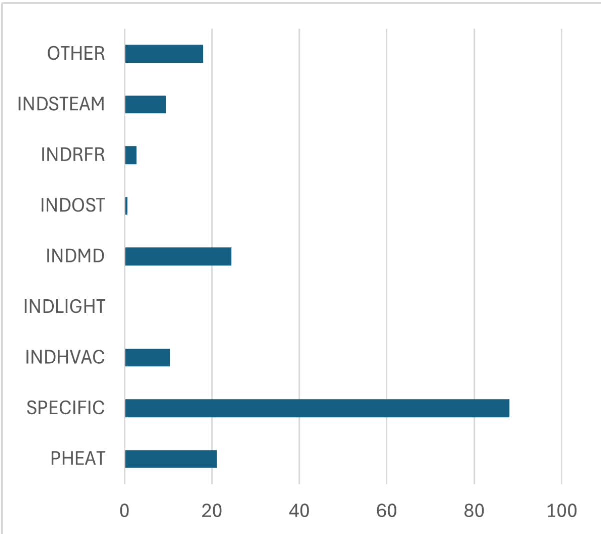

Figure 3.5: Industrial sector's useful energy demand distribution (PJ)

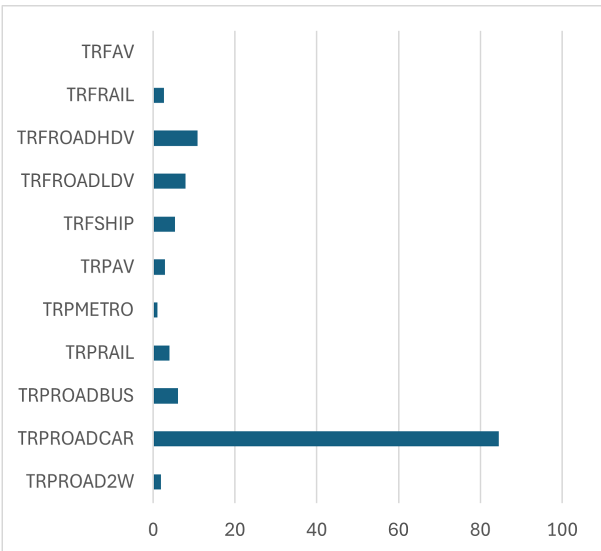

Figure 3.6: Transports sector's useful energy demand distribution (PJ)

Agriculture is the smallest contributor to the total demand with only 7.2 PJ and 57% is due to the demand for heating in this sector, as it is shown in figure 3.7. The second largest contributor is the demand for machinery, accounting for roughly a quarter of the total demand.

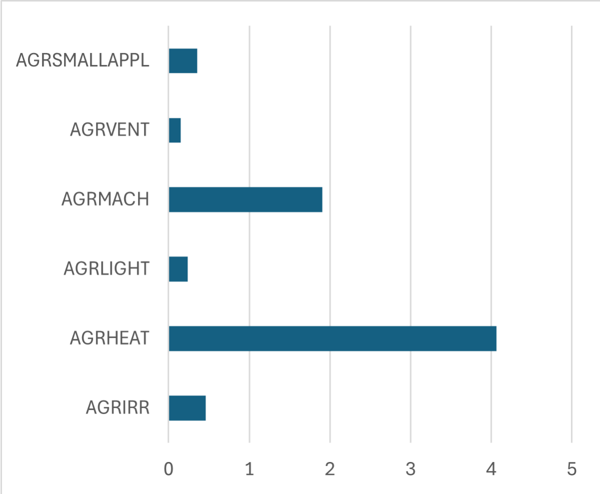

Figure 3.7: Agriculture sector's useful energy demand distribution (PJ)

3.3.2 Residual Capacity

In the base year, residual capacity is responsible for assuring the fulfilling of the demands. In this section, these capacities are analysed by sector, and, when convenient, the distribution for a specific end-use's technologies will also be considered.

3.3.2.1 Primary sector

As the sector that will provide the rest of the system, the analysis on the starting point for the residual capacities on this sector becomes of great importance. Figure 3.8 represents the share of each technology on the residual capacity for the primary sector. It is important to make evidence of the combined residual capacities of wind power plants and large hydrological power plants adding up to 49% of the total. The rest of the capacity is essentially composed of fossil fuel-based technologies, also featuring electricity imports. There is also a small representation of biogas and biomass plants for the prodution of electricity and/or heat and of the use of solar energy for the production of electricity and centrally produced heat.

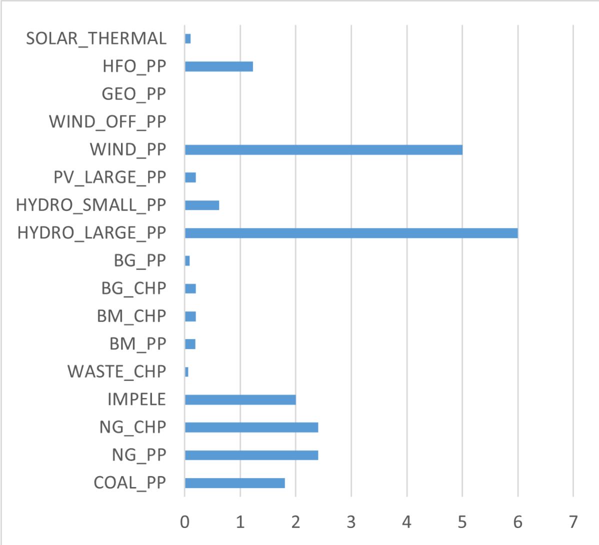

Figure 3.8: Primary sector's residual capacity distribution (GW)

3.3.2.2 Residential buildings sector

The residential sector, while being one of the most electrified ones, still has a great presence of other fuels like natural gas for cooking or biomass and oil products for space heating, this last one being represented in figure 3.9.

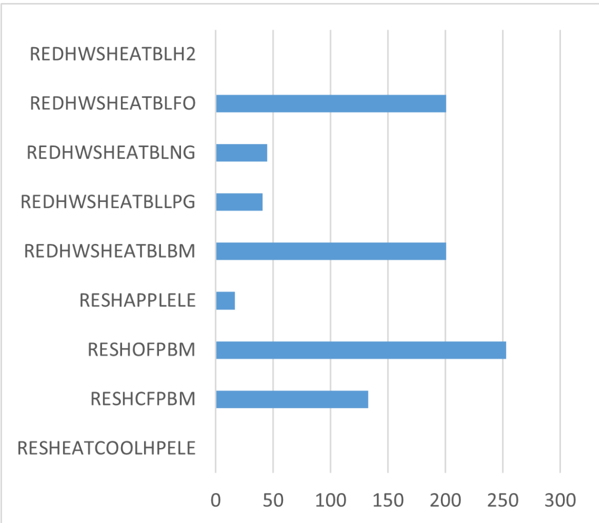

Figure 3.9: Distribution of the residual capacity for space heating technologies (PJ/year)

The figure evidentiates the remaining potential for electrification or other more environment-friendly solutions, such as hydrogen. Despite still having emissions for its utilisation, biomass has a much lower emission factor when compared to other energy carriers.

Another important aspect to point out is that some end-uses still do not have high efficiency technologies providing the demand. This is the case for lighting technologies' residual capacities, which, as it is represented in figure 3.10, is mainly composed by incandescent lightbulbs, a technology defined with 5% efficiency. The other two technologies that present residual capacity, halogen and fluorescent lightbulbs, show a higher efficiency (9% and 20% respectively) when compared with the incandescent ones, however are still especially far from the LED lightbulbs, which present an efficiency of 90%.

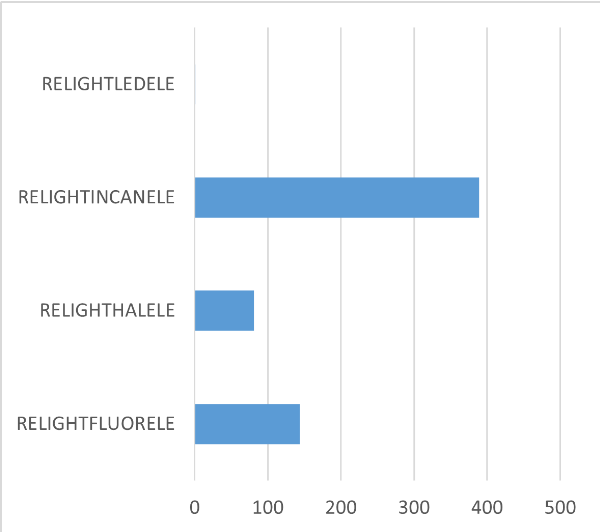

Figure 3.10: Distribution of the residual capacity for lighting technologies (PJ/year)

3.3.2.3 Services buildings sector

The services buildings sector, despite also having a great share of technologies that make use of natural gas and oil products, has a different distribution from the residential sector. For example, presented in figure 3.11 is the share of each technology for the total residual capacity in cooking technologies. In this sector, the majority of the residual capacity is composed by electrical cooking technologies, while in residential the equivalent demand is mainly fed by natural gas technologies.

Another difference is, for example, in the space heating and water heating residual capacities, where LPG and fuel oil boilers have practically 100% representation in the first end-use and 99% in the second one, this last one represented in figure 3.12.

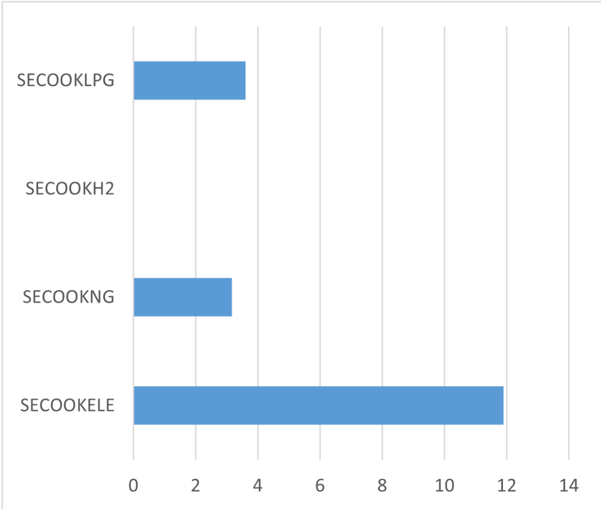

Figure 3.11: Distribution of the residual capacity for cooking technologies (PJ/year)

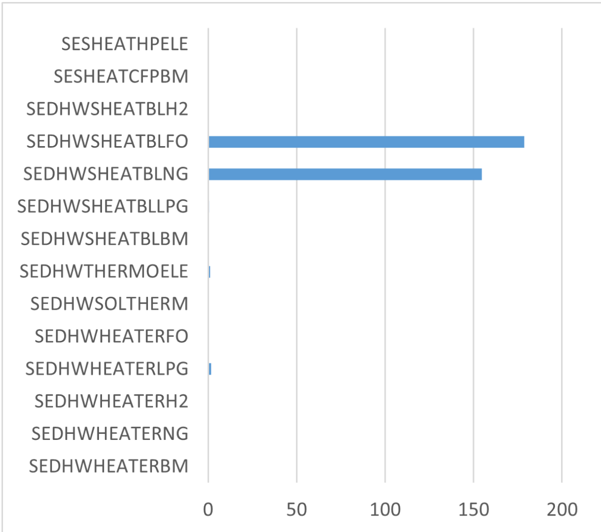

Figure 3.12: Distribution of the residual capacity for water heating technologies (PJ/year)

3.3.2.4 Industrial sector

This sector is mainly characterized for having specific uses, which mostly have only two alternative technologies to produce them, and some only have one. For some, the two alternatives are between being fuelled by natural gas or biogas (this last one has no residual capacity in any of the technologies), and for others the alternatives comprise cheaper low-efficiency and expensive high-efficiency technologies, which for this last case tend to be equally distributed or close. That is not the case for pulp production technologies, where chemical pulp production technologies have a weight of 71 % in total residual capacity, as depicted in figure 3.13.

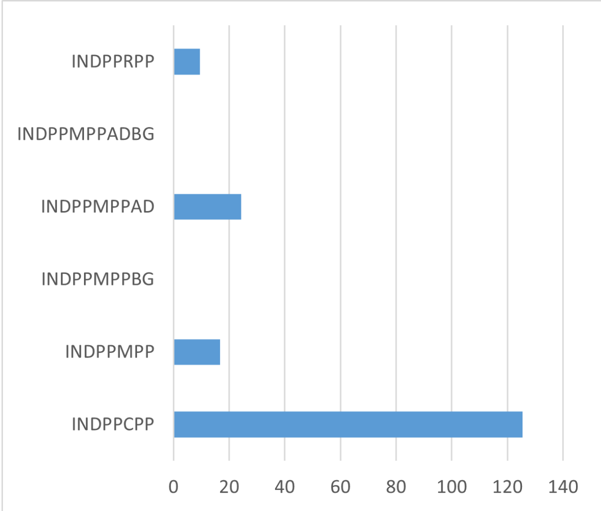

Figure 3.13: Distribution of the residual capacity for pulp production technologies (PJ/year)

For demands that apply generally to all the industry sub-sectors, the characterization is similar to the previous two sectors. There is also a big presence of natural gas and oil products technologies, as is the example of the distribution of the residual capacities of technologies that fulfill the HVAC needs, as illustrated in figure 3.14.

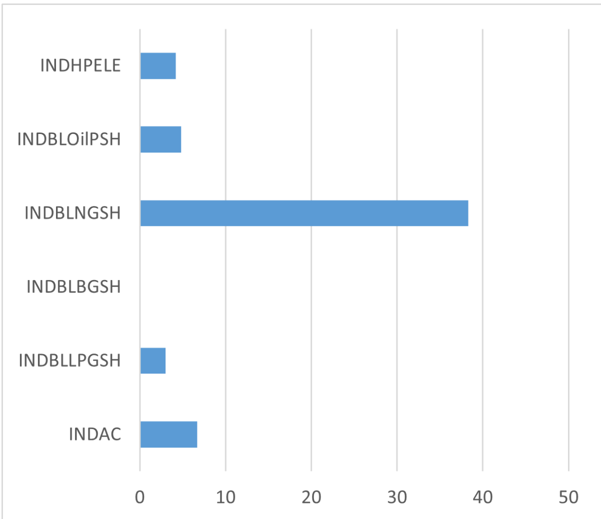

Figure 3.14: Distribution of the residual capacity for HVAC technologies (PJ/year)

One last note on this sector is the use of heat for the production of different end uses. A clear example would be the steam production residual capacities share for each technology shown in figure 3.15, where the boilers that make use of heat represent almost a half of the total residual capacity.

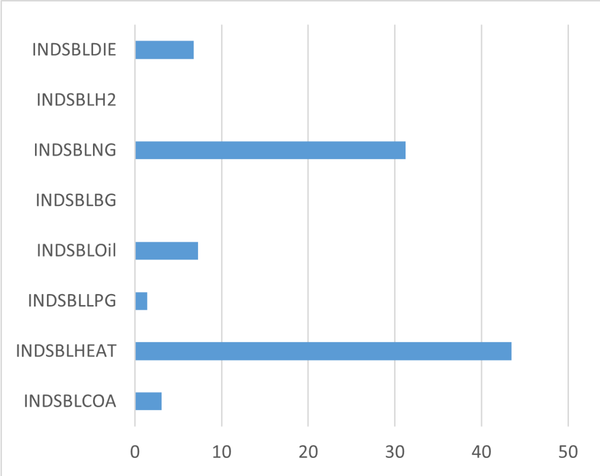

Figure 3.15: Distribution of the residual capacity for steam production technologies (PJ/year)

3.3.2.5 Transports sector

The transport sector is the one that considers more future technologies, i.e., technologies not present on the current system but that will come to the market in the future and need to be included in the model in order to better understand how the system can evolve. This leads to the fact that in several end-uses only one of the possible technologies is assuring the production. For example, in aviation only fuel oil using technologies have residual capacity.

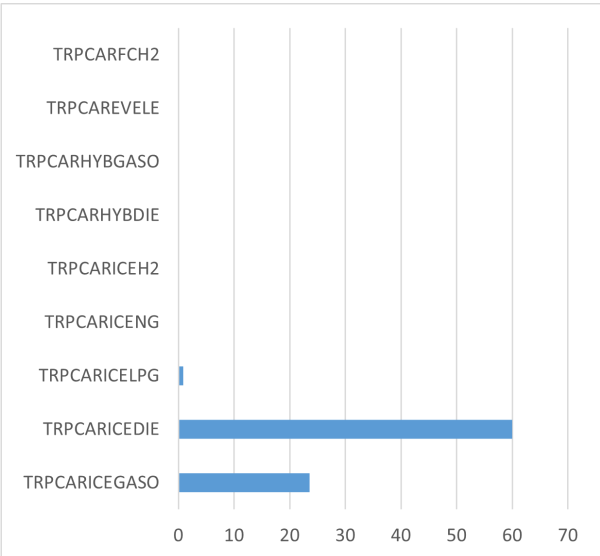

Figure 3.16: Distribution of the residual capacity for cars for road passenger transport technologies (PJ/year)

The best example of the representation of what fuels are used for the technologies is the residual capacity share for each road passenger transportation by car technologies, represented in figure 3.16. Apart from the rail technologies, which are already greatly electrified, the weight of oil products technologies is substantial, in this example reaching more than 99%.

3.3.2.6 Agriculture sector

This last sector shows similarities with the others in terms of having a great presence of fossil fuel technologies in the initial capacities. As an example, figure 3.17 representing the residual capacity for heat production technologies makes evidence of this fact, as 93% of heat production makes resource of diesel technologies.

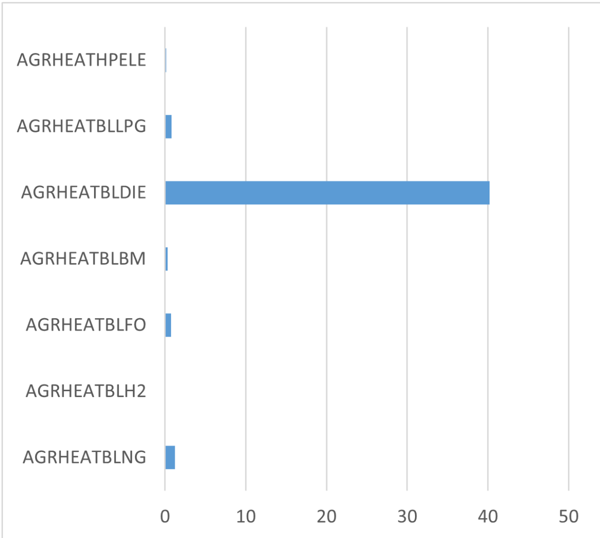

Figure 3.17: Distribution of the residual capacity for heating technologies (PJ/year)

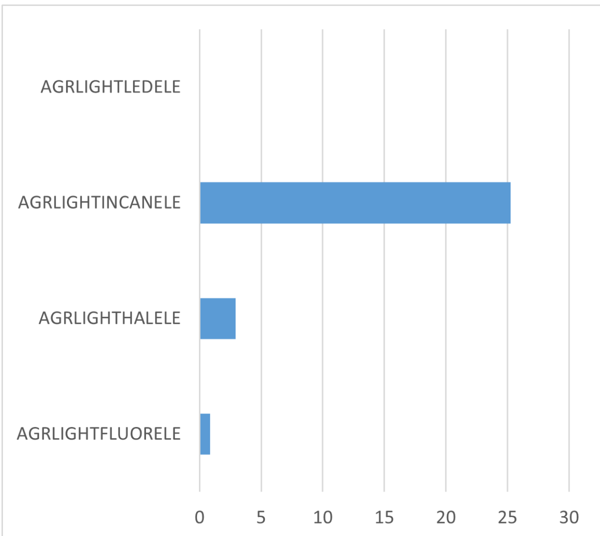

Figure 3.18: Distribution of the residual capacity for lighting technologies (PJ/year)

The same question that arose for the residential buildings sector with lighting takes place in this sector. Figure 3.18 shows that once again low efficiency technologies are highly present in the system.

3.3.3 Emissions

The emissions in the first year have a total of 54.3 MtCO_2eq, which is in line with the emission reported in RNC [1]. Figure 3.19 shows the share of emissions for each primary resource. The share of natural gas in the total emissions is immediately noticed, representing 49%. Following, the combined share for crude oil and oil products reaches 38%. With coal power plants still present in the base year, coal's share in the total emissions is of 11%.

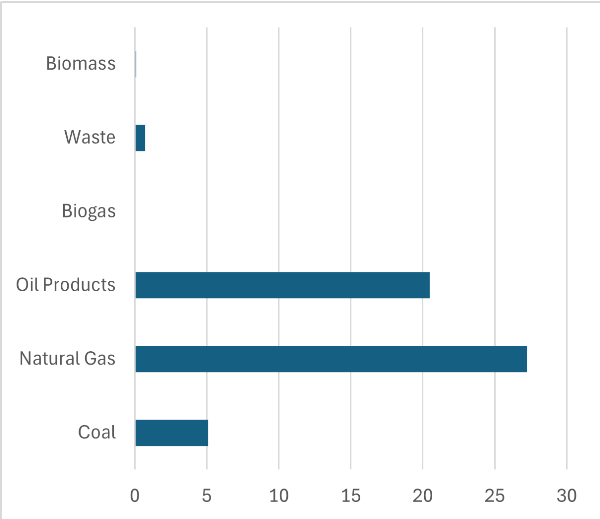

Figure 3.19: Distribution of the emissions in the base year for each primary resource (Mt CO_2eq)

3.4 Future scenarios

Creating scenarios consists of introducing variations to the model and evaluate its response to these changes. In energy modelling, if generated adequately, the scenarios can provide the analyst with clues to how the real energy system needs to evolve in order to meet certain goals. In this model, the definition of the scenarios starts with the designation of the base scenario, evolving then to the different changes that are going to be applied.

3.4.1 Scenario Business as Usual

The Business-As-Usual (BAU) scenario consists of giving no limitations to the model. This scenario evaluates how the system would evolve if the only objective was to lower the total costs as much as possible. It does not consider any emission limit, however considers penalties for emissions. The model will follow an optimisation path which will represent the minimum cost for the system. This scenario will be the reference when analysing the results of the alternative scenarios. As a baseline for the alternative scenarios, the carbon costs, i.e., the penalties for emitting greenhouse gases specific to each year, are depicted in Table 3.3. The years on the table are representative of the evolution of the carbon costs throughout the planning horizon. With all of the values being in M€/MtCO_2eq, the carbon costs start with 8 and practically maintaining until 2018, where in two years it practically doubles twice. The evolution is then uniform until 2022, where it remains constant for one year and increasing slightly in 2024. Between 2024 and 2038 it has a yearly increase of two. From 2038 it remains constant.

Table 3.3: Carbon costs evolution, M€/MtCO_2eq

Year	2015	...	2018	2019	...	2022	2023	2024	2038	...
Carbon Cost	8	...	18	30	...	56	56.2	58	88	...

3.4.2 Alternative scenarios

The goal of this study is to evaluate different pathways that can be followed aiming for the energy sector's self-sufficiency. With this in mind, six different scenarios were developed in order to assess how the system would respond to different limits or variations that could be imposed. These scenarios will be based on changing three different parameters which are: emission limits, activity limits and emission penalties. A comparison between all the scenarios is represented in Table 3.4. Setting an emission limit and high emission penalties follows the same principle: fossil fuels, which are responsible for almost all the emissions, are all imported, so, by forcing the model to reduce its emissions or by giving them high penalties, it should consequently reduce the imports. Activity limits are more straight to the point, as the model is forced to reduce the imports. These will not be representative of possible policies to establish, but will present how the energy system will evolve while reducing imports to certain levels.

The only difference imposed on the first alternative scenario is an emission limit for 2050. This value follows the one defined as an objective for 2050 in order to reach carbon neutrality [1]. Following this scenario, come three others that represent variations for the definition of the carbon costs.

Table 3.4: Scenarios definition

Scenario	Emission Limits	Carbon costs	Activity Limits on imports
BAU	No	Regular	No
EmLim2050	Yes, in 2050	Regular	No
HighCost2035	No	High, starting from 2035	No
VeryHighCost2035	No	Very high, starting from 2035	No
HighCost2040	No	High, starting from 2040	No
ActLimEle	No	Regular	Yes, including electricity
ActLim	No	Regular	Yes, excluding electricity

Of the three, the base one is denominated as *HighCost2035*, where the carbon cost in 2035 is set to 150 and increasing linearly until reaching 200 in 2050. From this, the next two scenarios follow by increasing the new carbon cost to the double, and by setting the start year for the new carbon cost to be in 2040. The last two scenarios are relative to imposing limits on the activity of the imports technologies, for one limiting electricity import and for the other not limiting. This variation is due to the fact that as Portugal only imports electricity directly from Spain, so the reasons for self-sufficiency almost drop completely, due to the high level of collaboration with this country and the stable diplomatic relations established with it. The only exception for these activity limits is biogas. Identified as the main (and sometimes the only) alternative for natural gas in several technologies, it would be counterproductive to also limit it. To set the activity limits for the imports, an assessment to their values for the base year was carried out. In order not to conflict with the minimum activity values set for the end-use technologies, the limitation for activity only starts from 2021. Prior to this year, the limit is set to equal the base year activity values, which in all previous optimizations showed to be the year with the maximum values for their activity. The limits were defined as 10% of the activity in the base year for 2050, decreasing linearly between 2021 and 2050. For electricity imports, the limit was imposed taking into account the maximum activity possible for the maximum installed capacity. This is the limit set between the base year and 2020, from which it follows the same approach as the other imports technologies.

Chapter 4

Results and Discussion

In order to better visualise the outcomes of the various scenarios, the results were examined. The outcomes of that examination will be described in the following sections. For the sake of simplicity for the presentation of the results, several end-uses were chosen based on their representativeness of the other end-uses. The analysis will start with a full description of the results for the BAU scenario, moving on to a comparison between the alternative scenarios and the base one, and ending in an overview of what the results represent and final considerations on the effects of the changes introduced in the alternative scenarios. It is important to note that the end-uses that can only be provided by one technology, such as the production of cement in the cement and lime industry, are not going to be analysed, as their evolution will only follow the demand's evolution.

4.1 BAU scenario

4.1.1 Evolution of the energy system

4.1.1.1 Primary sector

The primary sector includes the production of the main carriers required by the end-use sectors. Starting with electricity production, represented in figure 4.1, the production is mainly guaranteed by natural gas cogeneration plants, with a smaller representation of electricity generated by hydropower plants and wind power plants. Starting in 2020, the imports of electricity have an increasing trend, reaching their maximum in the last years of the planning horizon. The production of centralized heat was found to be similar, with a high percentage of natural gas cogeneration plants, and the rest distributed between biomass and biomethane cogeneration plants. The evolution of the installed capacities of the technologies that are able to produce each energy carrier follows the same pattern as its production, thus only the representation for the evolution of production for each technology by energy carrier will be presented, and the installed capacities are assumed equivalent.

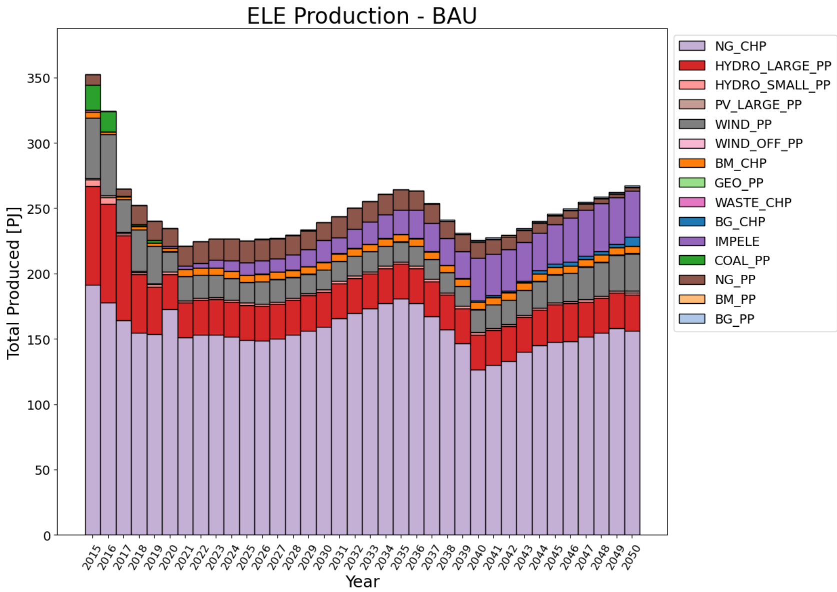

Figure 4.1: Evolution of electricity production in the primary sector for the BAU scenario

As depicted in figure 4.2, the production of hydrogen has an increasing trend, starting by being produced from natural gas steam reformers and, in the last years, from electricity using solid oxide electrolyzer cells. This increasing trend is due to the higher use of hydrogen-fuelled technologies.

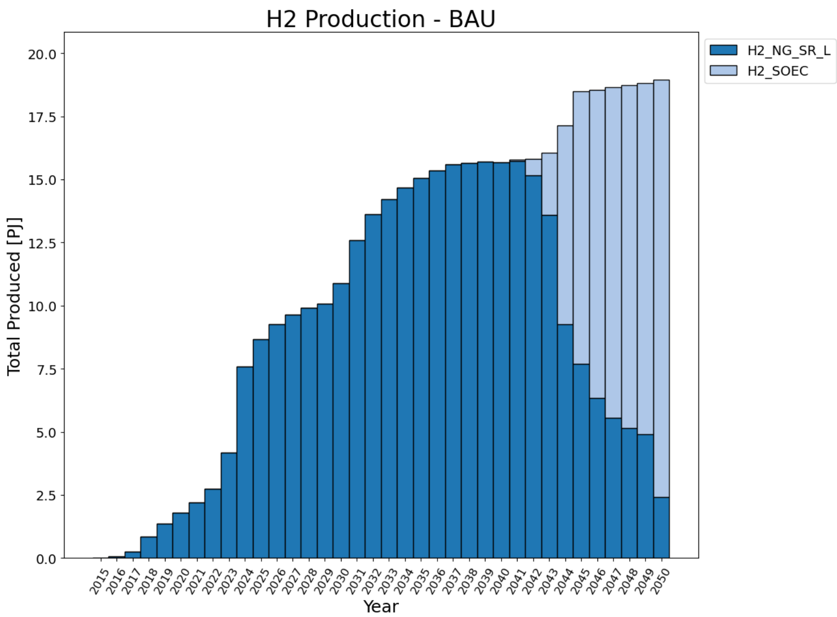

Figure 4.2: Evolution of hydrogen production in the primary sector for the BAU scenario

Despite being more expensive, the electrolyzer cells technologies allows for a reduction of the use of natural gas, thus reducing the emissions penalties.

In the production of oil products, diesel is representative of all the other products. Figure 4.3 shows that in the first years there is still a presence of locally refined diesel, but is eventually completely substituted by its import. As use of diesel in the end-use sectors is not proportional to the ones for the other oil products (as well as their evolution), it becomes more expensive to produce an excess of the other oil products when compared to the costs of importing diesel directly, and so the system transitions to a full importing system when accounting for the production of diesel.

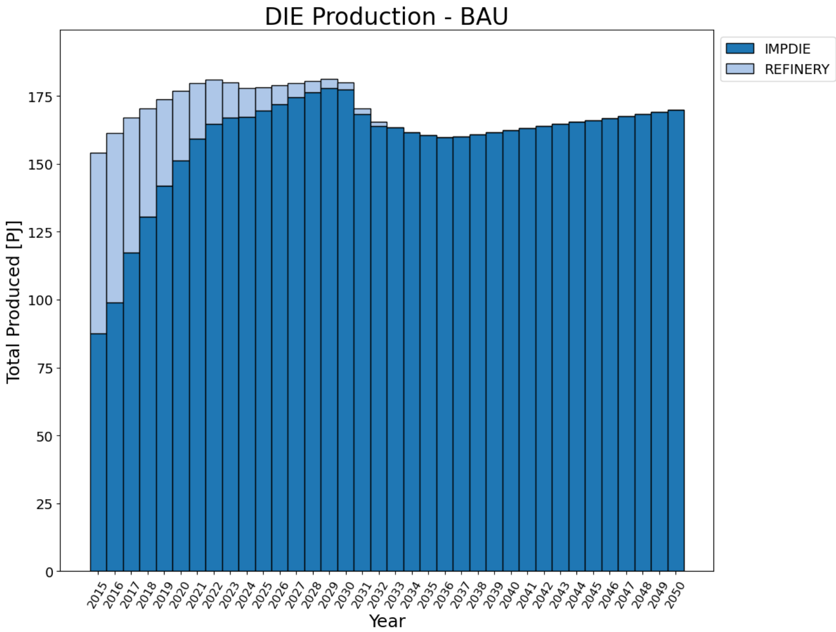

Figure 4.3: Evolution of diesel production in the primary sector for the BAU scenario

4.1.1.2 Residential buildings sector

In residential buildings, the second highest demand is represented by water heating following the transition shown in figure 4.4. Two major aspects can be noted, with the first being that the replacement of the the residual capacity is assured by one main technology: biomass heaters. The second one is that the trend in the final years of the planning horizon, these heaters start being substituted, and water heating in the last year is mainly produced using centralized heat and thermoaccumulators (commonly referred to as water heaters). Lower costs and higher efficiencies of these technologies make them more appealing to fulfill the demand.

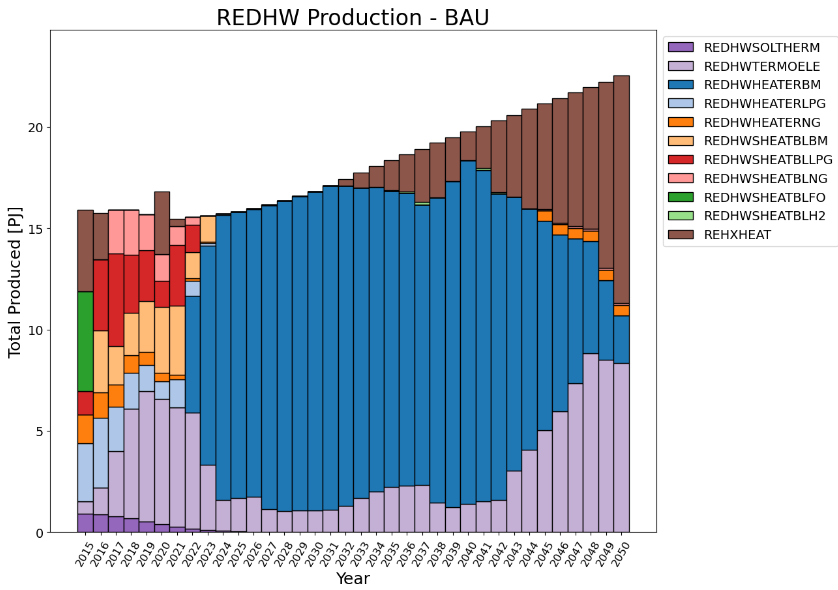

Figure 4.4: Evolution of water heating production in the residential buildings sector for the BAU scenario

Several end-uses in this sector are produced only by electricity fuelled technologies. One example of this is dishwashing, the production of which is shown in figure 4.5. Similarly to clothes washing, refrigeration and lighting, the trend is to shift away from the production of this end-uses by low efficiency technologies, towards high efficiency technologies even before half of the planning horizon. Despite higher capital costs, high efficiencies technologies will help to bring down the overall costs by reducing the use of electricity, thus reducing variable costs attributed to fuels.

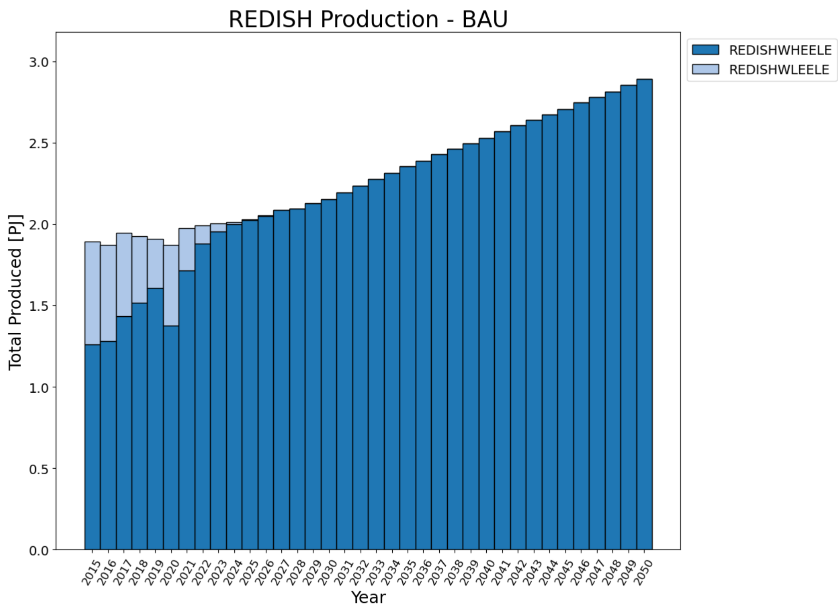

Figure 4.5: Evolution of dishwashing production in the residential buildings sector for the BAU scenario

The highest demand in the residential buildings sector is attributed to space heating. Its production evolution is shown in figure 4.6. In the first years the trend is to use the same technologies that were established in the residual capacity, with a focus on fuel oil boilers and small heating appliances. However, from half of the planning horizon, the trend is to produce all the required energy making use of heat pumps. This trend is also present in space cooling production. Despite not as high as the ones on the other scenarios, the emissions penalties on the BAU scenario still promote the system to transition towards a cleaner energy use and high efficiency one, such as what happens with heat pump, which are fuelled by electricity and present high efficiency values.

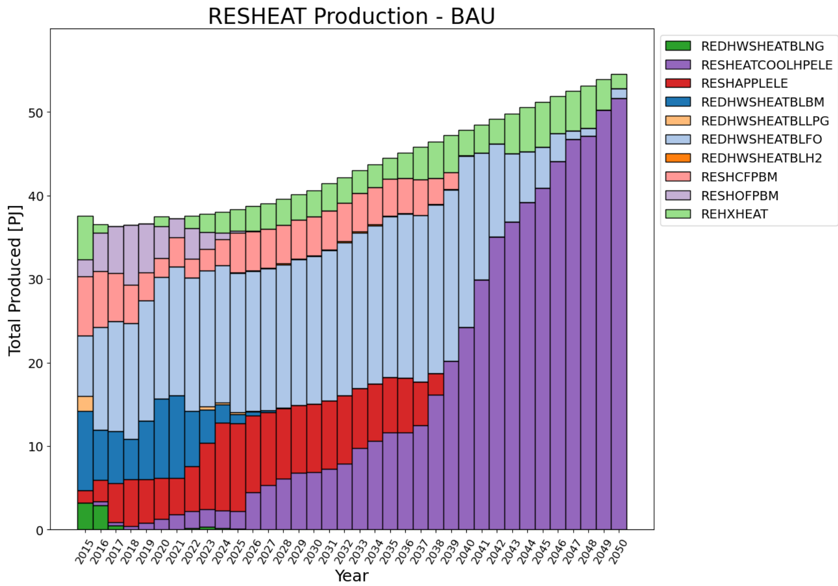

Figure 4.6: Evolution of space heating production in the residential buildings sector for the BAU scenario

4.1.1.3 Services buildings sector

Given the similarity in terms of end uses and technologies in the residential (buildings) sector and the commercial (buildings) sector, there are some expected similarities in the results for these two sectors. One example is depicted in figure 4.7, which shows evolution of the production of the demand for freezing. Similarly to the residential sector, for end-uses that resort only to electricity, the trend is to substitute low efficiency technologies by high efficiency ones, well ahead of the halfway mark in the transition to 2050. The same trend is observed for clothes washing, dishwashing, refrigeration and lighting for this sector.

One difference to the previous sector was found in the production of water heating, represented in figure 4.8. In this case, the production from residual capacity reaches end of life earlier, and is immediately replaced by thermoaccumulators, which only happened in the last years for the residential sector. There is also a representation of centralised heat in the production of this end-use.

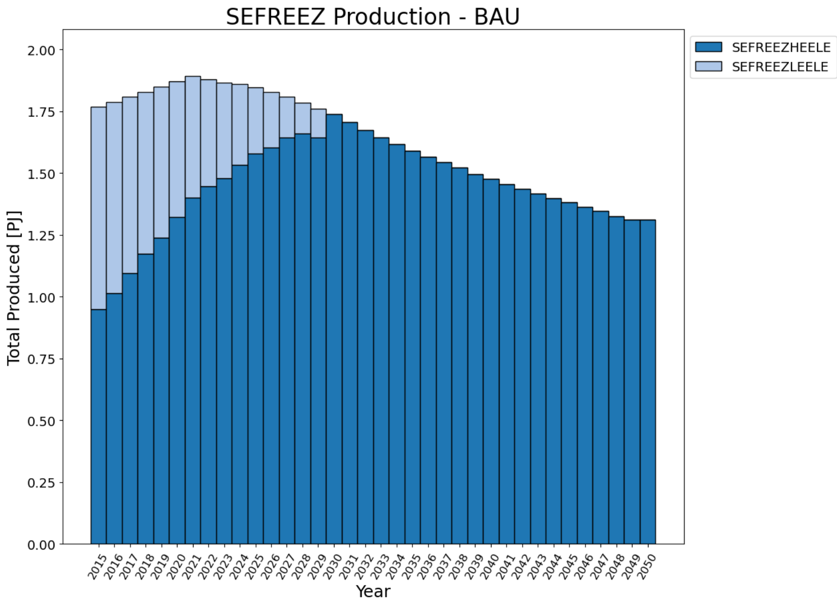

Figure 4.7: Evolution of freezing production in the services buildings sector for the BAU scenario

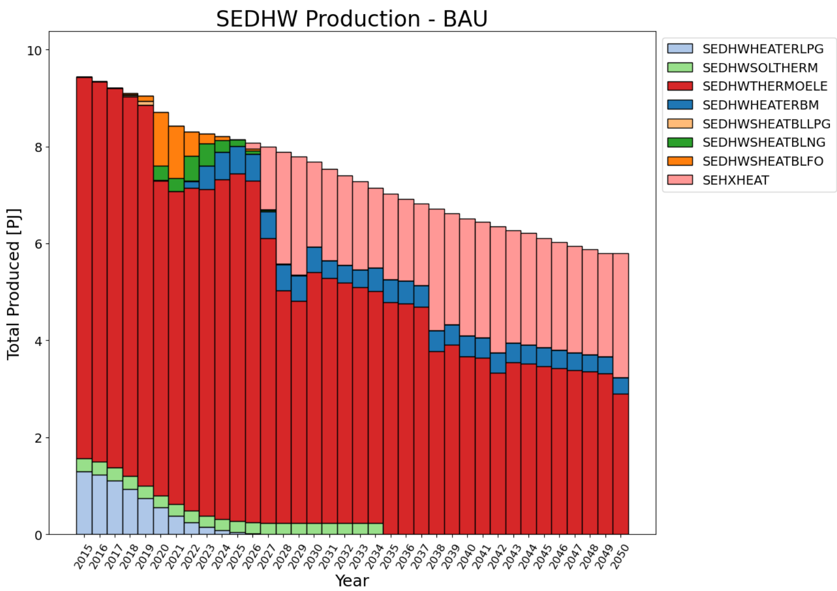

Figure 4.8: Evolution of water heating production in the services buildings sector for the BAU scenario

Another difference between the residential and the commercial sector is the cooling end use shown in Figure 4.9. While in the previous sector heat pumps become the dominant technology, in commercial buildings the production of cooling is evenly distributed between heat pumps and centralised air conditioners. The production of space heating, on the other side, follows the same pattern as the one verified in the residential buildings sector. Both heat pumps and centralzied air conditioners are technologies with very high efficiencies, which makes them in optimal options for the overall costs.

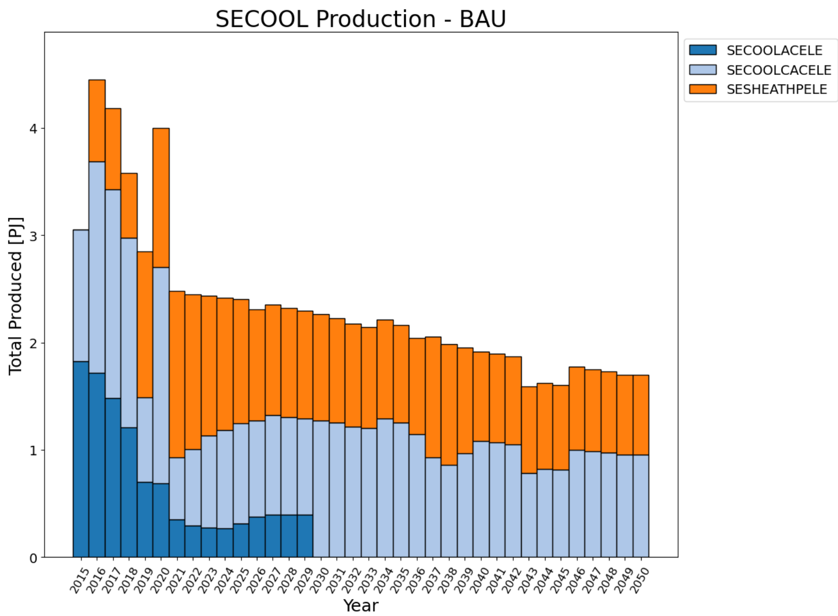

Figure 4.9: Evolution of cooling production in the services buildings sector for the BAU scenario

4.1.1.4 Industrial sector

The industrial system is especially characterized by having end-uses that have few alternative technologies. However, there are some that have multiple options, such as process heat production provided by boilers, depicted in figure 4.10. With variations for each year, the system tends to keep the same technologies that were present in the residual capacity, emphasizing the use of biomass. In the last 15 years of the planning horizon, the system starts to invest in very high efficiency biomass boilers, with these becoming the predominant technology, with a slight contribution from very high efficiency biomethane boilers. These two technologies make use of fuels with lower emission ratios, which contributes to reducing the overall costs by reducing emissions penalties.

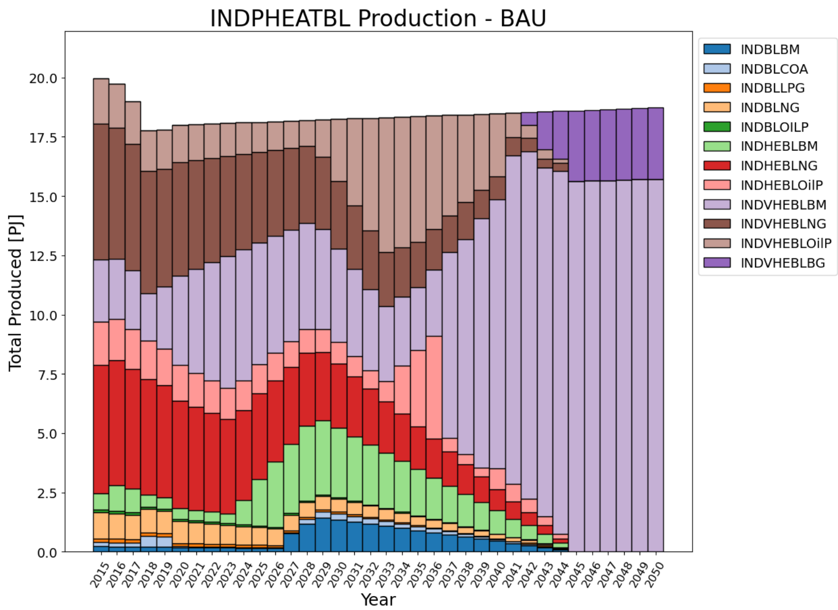

Figure 4.10: Evolution of process heat production from boilers in the industrial sector for the BAU scenario

Process heat production by ovens is used in the food and beverages industry, where, as shown in figure 4.11, electrical ovens dominate the production until the last 5 years.

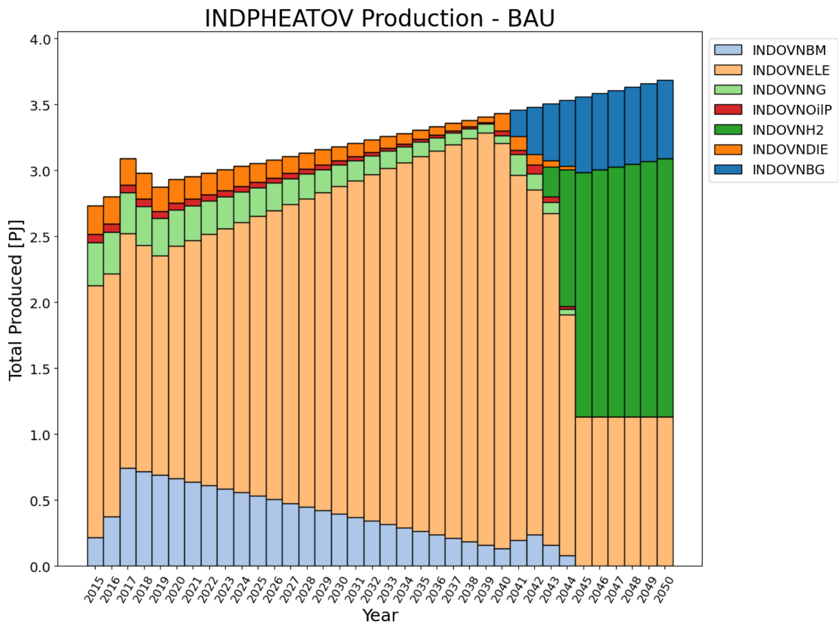

Figure 4.11: Evolution of process heat production from ovens in the industrial sector for the BAU scenario

In these years, investments on hydrogen and biomethane ovens are carried out, with them producing roughly two thirds of this end-use in the last year. These two technologies are introduced in the system due to their lower price. The production of process heat by kilns follows the same pattern of investments, with the exception of the investment on hydrogen technologies.

An end-use that is applicable to several industries is steam. Its production is represented in figure 4.12 and evolves with the technologies present in the residual capacities being replaced by coal fuelled steam producing boilers, with this technology being dominant in the last year of analysis. This is due to the fact that coal technologies have considerably lower costs for this end-use. The same pattern repeats in HVAC, steel and process heat production by kilns in the cement and lime industry, where the main installed capacity makes use of fossil fuels.

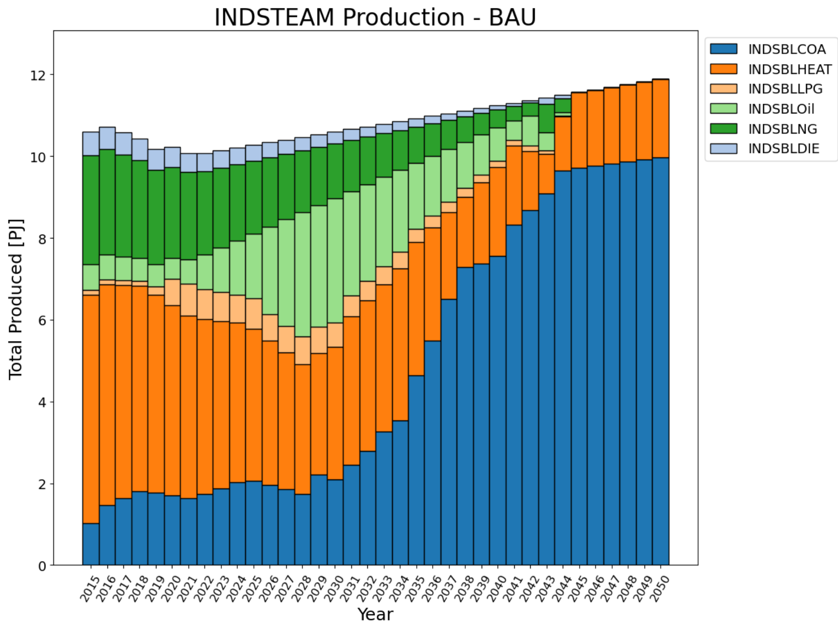

Figure 4.12: Evolution of steam production in the industrial sector for the BAU scenario

One of the biggest patterns in the industrial sector, as shown in figure 4.13 for the production of pulp in the paper and pulp industry, is the substitution of the initial capacities for the industry specific end-uses, mainly reliant on natural gas, by technologies that make use of biomethane. The same happens for crude steel, aluminium, crude aluminium, flat glass, hollow glass and ammonia productions.

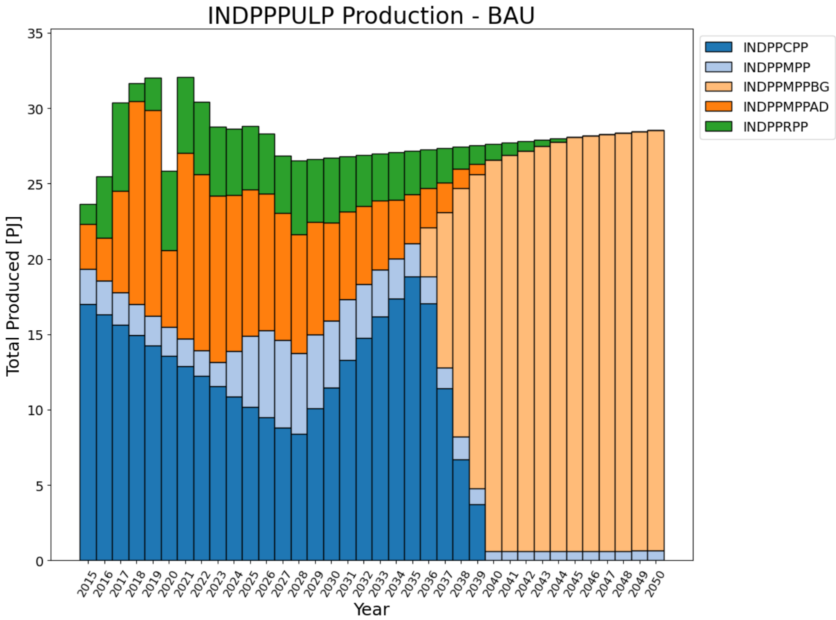

Figure 4.13: Evolution of pulp production in the industrial sector for the BAU scenario

For end-uses satisfied by technologies that make use of electricity, the trend is to substitute low efficiency capacity by high efficiency technologies, similarly to the previous end-uses. An example is shown for the production of chlorine in the chemical industry, depicted in figure 4.14. The same happens for lighting.

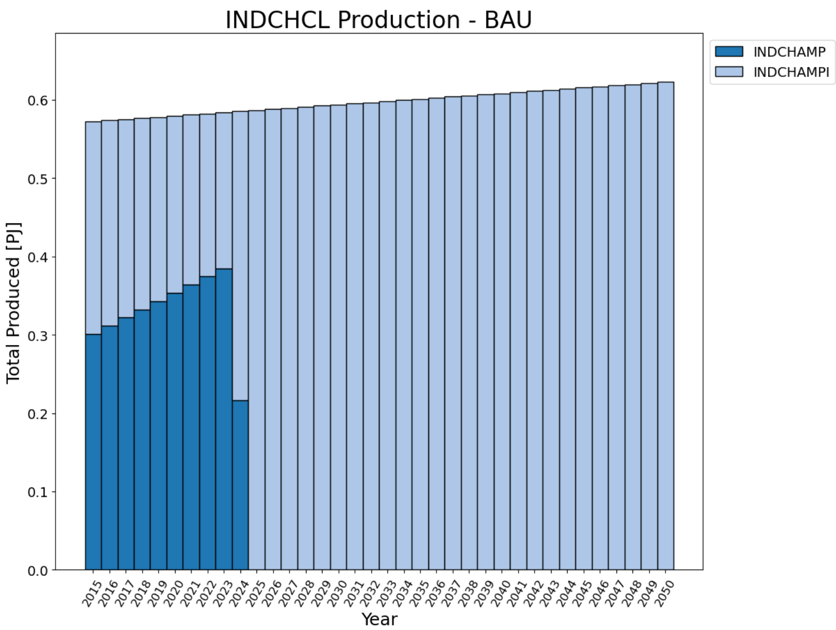

Figure 4.14: Evolution of chlorine production in the industrial sector for the BAU scenario

4.1.1.5 Transports sector

Characterized by an overwhlemingly dependence on oil products, the transports sector is considered as one of the main contributors to national GHG emissions and for a high level of reliance on exogenous resources. The results for this sector showed three different trends, with the first represented by the production of passenger road transport by cars, depicted in figure 4.15. In this case, the system makes no effort in abandoning fossil fuel technologies, as they are considerably cheaper than their alternatives. The same happens for freight road transport by light duty vehicles and freight aviation transport, with a slight difference for this last one where an electricity technology is mildly introduced in the end of the planning horizon. In this scenario, due to the low costs of both diesel and the diesel using technologies, the system establishes the full capacity with these last technologies. This will present to be one of the the end-uses with the more drastical difference between scenarios, as some will switch to fuels with practically no emissions to cope with the limits on imports and emissions, while the other will still maintain the use of diesel as the growth in the carbon costs does not overcome the costs of investing in alternative technologies.

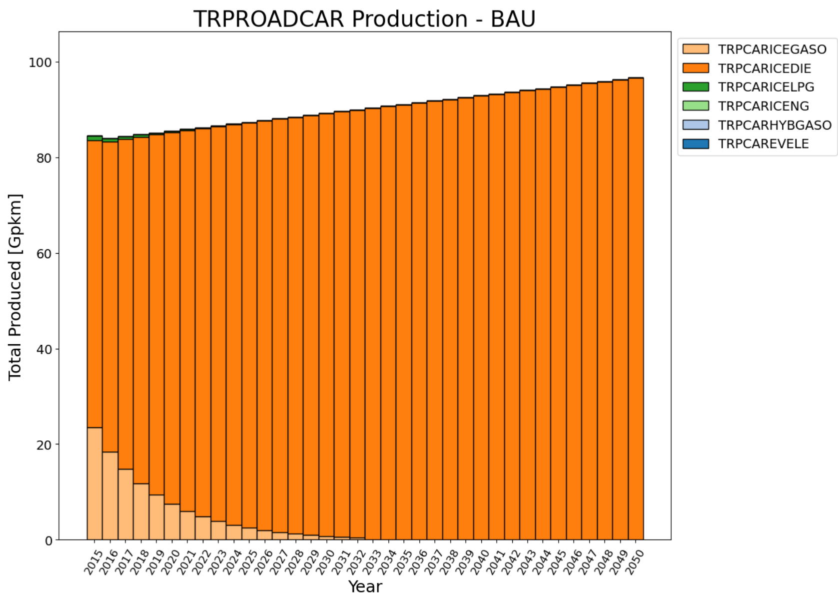

Figure 4.15: Evolution of passenger road transportation by car in the transports sector for the BAU scenario

The second trend, as exemplified for the passenger road transport by 2 wheel vehicles in figure 4.16, is characterised by the electrification of the end-uses.

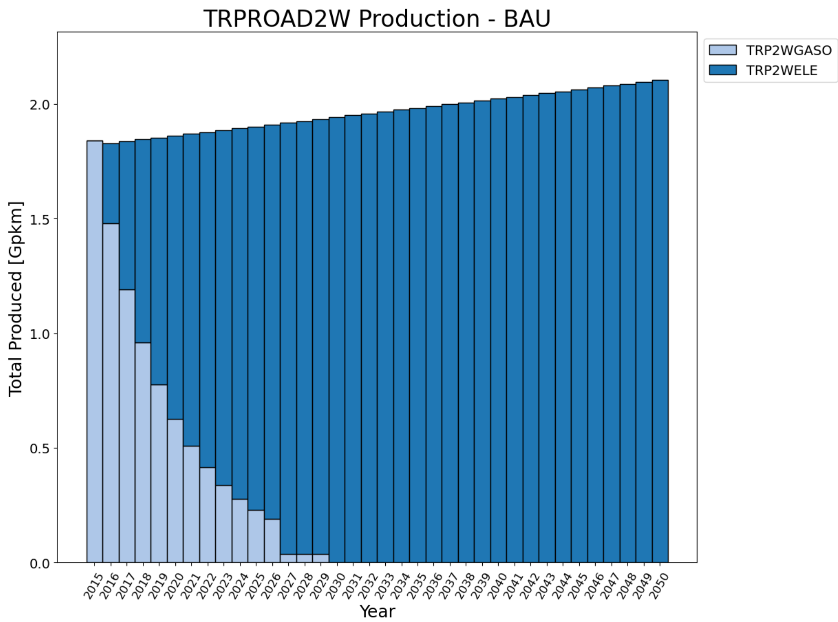

Figure 4.16: Evolution of passenger road transportation by 2 wheels vehicles in the transports sector for the BAU scenario

Right in the beginning of the time-frame of analysis, as residual capacity decreases, the system uses electricity-fuelled technologies to substitute it. Passenger rail transport, passenger aviation transport and freight rail transport follow the same pattern. The higher costs of electrical technologies, once more, undercut the costs of the emissions penalties.

The last trend represents the introduction of hydrogen in the final energy consumption of this sector, just as described in figure 4.17.

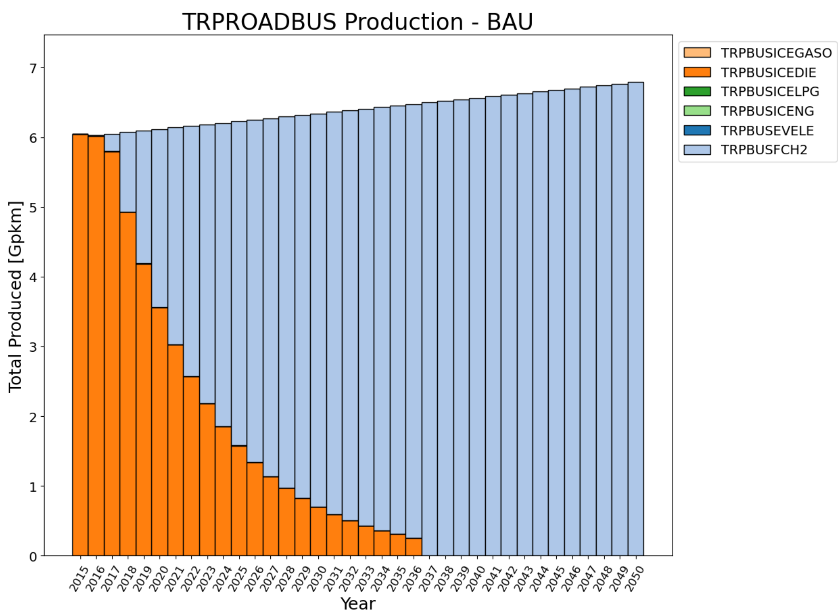

Figure 4.17: Evolution of passenger road transportation by bus in the transports sector for the BAU scenario

Tthe production of passenger road transport by bus abandons fossil fuels consumption and transitions to a full production coming from hydrogen fuelled technologies. The same happens with road freight transport by heavy duty vehicles and freight shipping transport, with a slight difference for the last one as the residual capacity is still very big in the last years, thus hydrogen technologies do not represent such a high share of the total production.

4.1.1.6 Agriculture sector

The agriculture sector is the least energy intensive one, but is still worthy of an in-depth analysis. With a great initial share of diesel consumption technologies, the heat production follows the evolution described in figure 4.18. This representation makes evident that hydrogen fuelled technologies substitute the existing ones, assuming full production from 2030. Despite not presenting high values for the emissions penalties, still in the BAU scenario the trend establishes in substituting fossil fuels with hydrogen, which might be explained due to lower costs of operating these technologies.

The other two end-uses of interest are irrigation and machinery, for which the evolution of the production follows the same trend. As depicted in figure 4.19, the existing technologies that make use of fossil fuels are completely substituted by electrical ones. Lighting production follows the same evolution as for the other sectors.

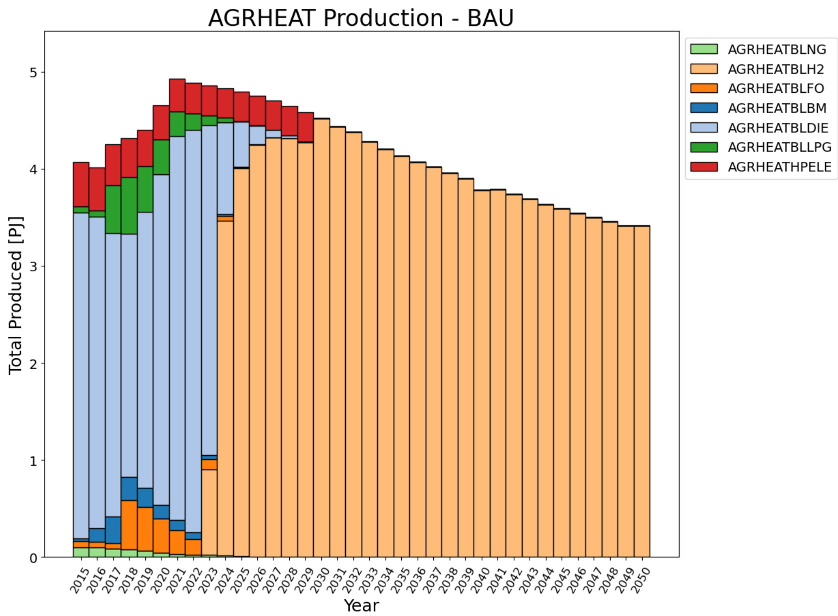

Figure 4.18: Evolution of heat production in the agriculture sector for the BAU scenario

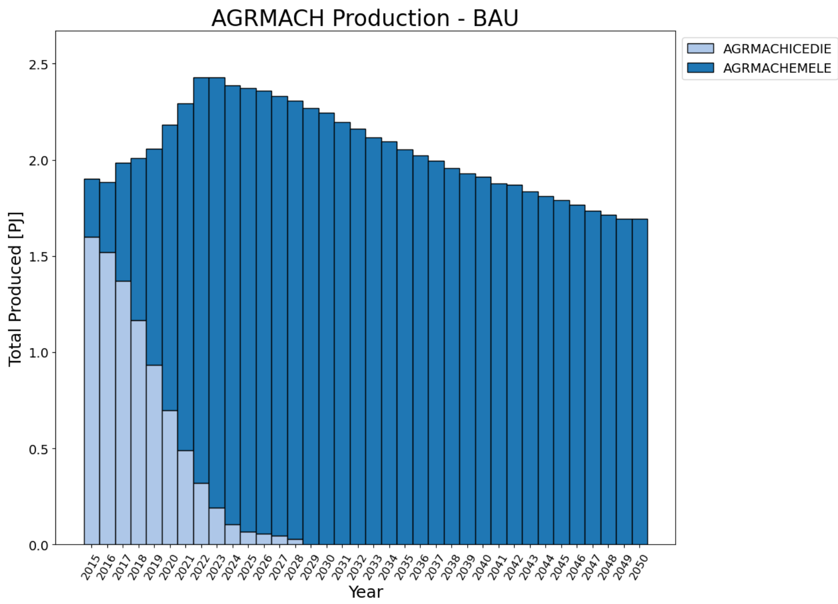

Figure 4.19: Evolution of machinery production in the agriculture sector for the BAU scenario

4.1.2 Emissions

The assessment of the evolution of the annual emissions produced by the system is an important aspect to consider, in order to compare with the objectives that are stated for decarbonisation. For this scenario, this evolution is represented in figure 4.20, which shows a general decreasing trend. There is an intermediate increase in the emissions, with a peak in 2035, which is coincident with an increase in the electricity production for those years. However, this decrease is not enough to meet the reduction targets defined for 2050.

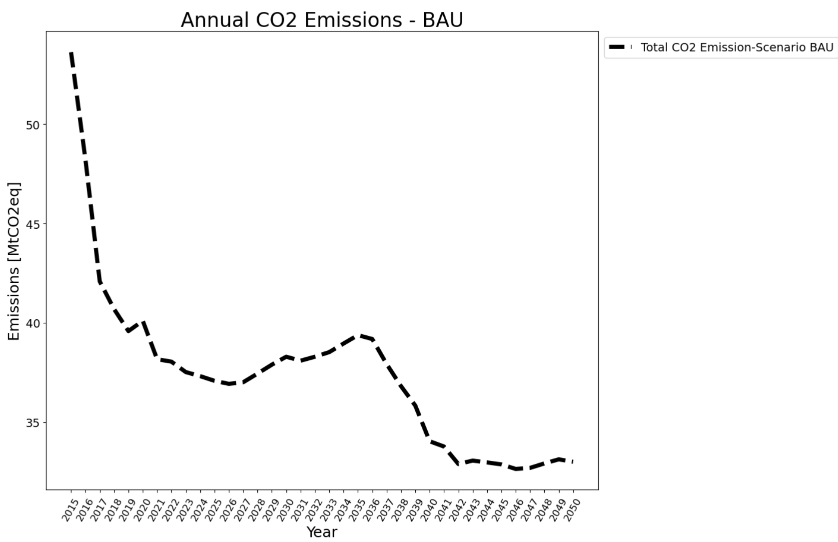

Figure 4.20: CO_2 annual emissions evolution for the BAU scenario

It is also interesting to carry out an analysis on the share of each primary resource in the total emission, and their evolution. This analysis is made easier by figure 4.21. It shows that the main contributor to the emissions is always natural gas with roughly half or more for each year. Crude oil and oil products are responsible for almost all the rest of the emissions, with coal contributing always with a small share. Note that, in line with what was concluded from the analysis on the production of diesel, crude oil's share disappears almost completely in 2030.

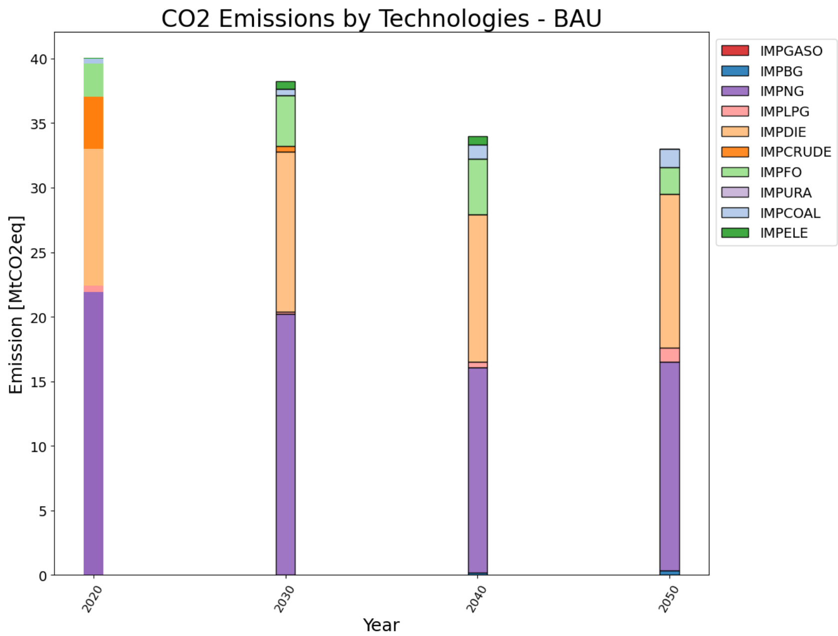

Figure 4.21: Technologies' shares evolution in CO_2 emissions for the BAU scenario

4.1.3 Costs

The analysis on costs indicates when the investments were made and in what volume they were made. Figure 4.22 shows the evolutions of costs, as well as a separation between capital, fixed and variable costs, for the electricity production technologies. The two peaks in 2015 and in 2040 for the capital costs jump to sight, but this is easily explainable as OSeMOSYS sets a default discount rate. The cost of the technologies is discounted in every year and, if the evolution of costs does not undercut the discount, the system will invest in full new capacity in one year, even if it only makes use of the technologies a few years after.

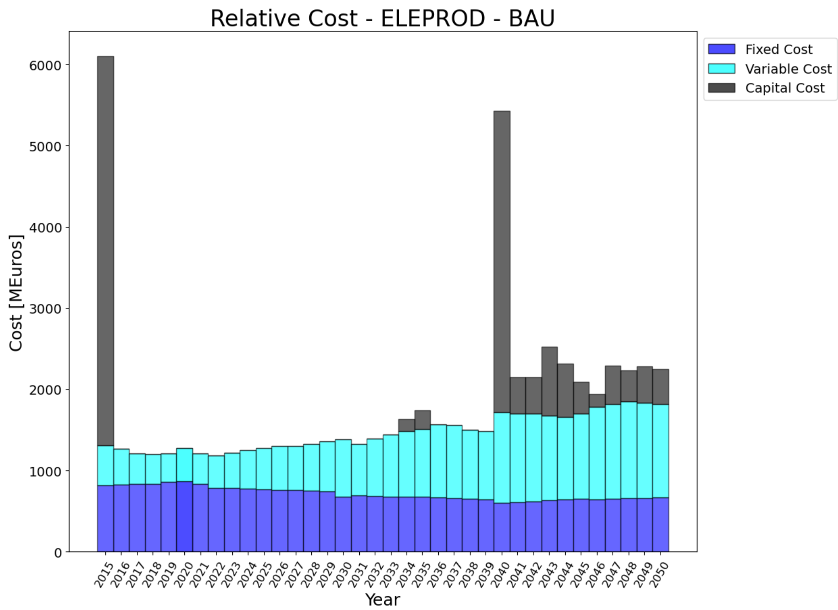

Figure 4.22: Costs evolution for the BAU scenario

4.1.4 Imports

As the main goal of this study was to assess how the Portuguese energy system could evolve towards self-sufficiency, it is necessary to evaluate how the imports will evolve during the planning horizon. This is represented in figure 4.23, which shows that despite a decrease in the initial years, the imports tend to stabilize in values around 600 PJ of primary energy, which are already lower values when compared with the initial 800 PJ.

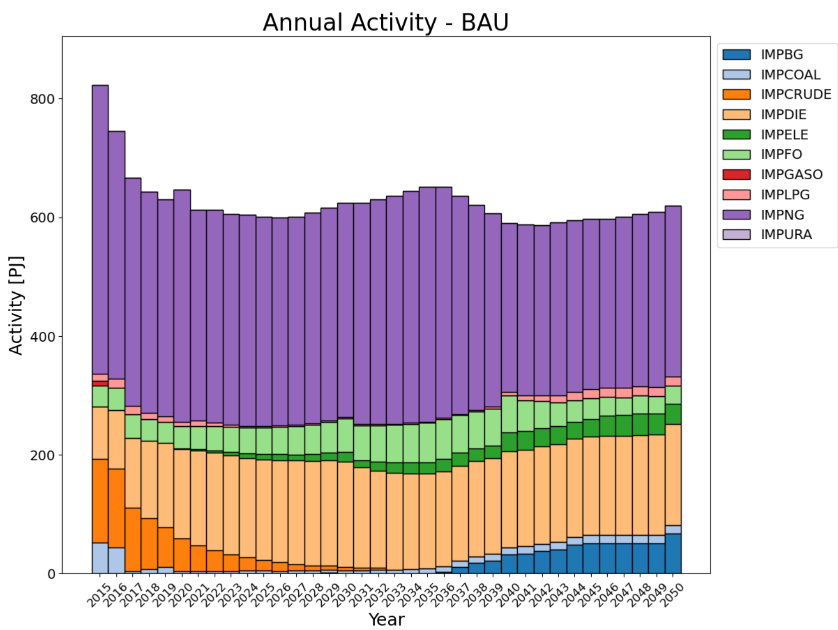

Figure 4.23: Technologies' shares evolution in the imports for the BAU scenario

4.2 Alternative scenarios

In this section, a comparative analysis between the scenarios results will be carried out. The same simplification for the choice of end-uses was considered, as they again present very similar results. The end-uses of analysis will be same as the ones considered for the other scenarios. There is no caption for the scenarios in the figures representing the outcomes of the scenarios. However, they will always follow the same order, from left to right: BAU, EmLim2050, HighCost2035, HighCost2040, VeryHighCost2035, ActLim and ActLimEle. The non existence of the captions of the scenarios is attributed to the utilization of a visualization tool developed by the research group that does not possess this capability.

4.2.1 Evolution of the energy system

The relation between production and capacity still applies here, so, similarly to the previous section and in order to establish the best comparison possible with BAU scenario's results, the results will be provided for production only.

4.2.1.1 Primary sector

In the primary sector, the production of the same carriers as in the BAU scenario will be compared, with the addition of heat production. For electricity production, figure 4.24 shows how the different scenarios behave.

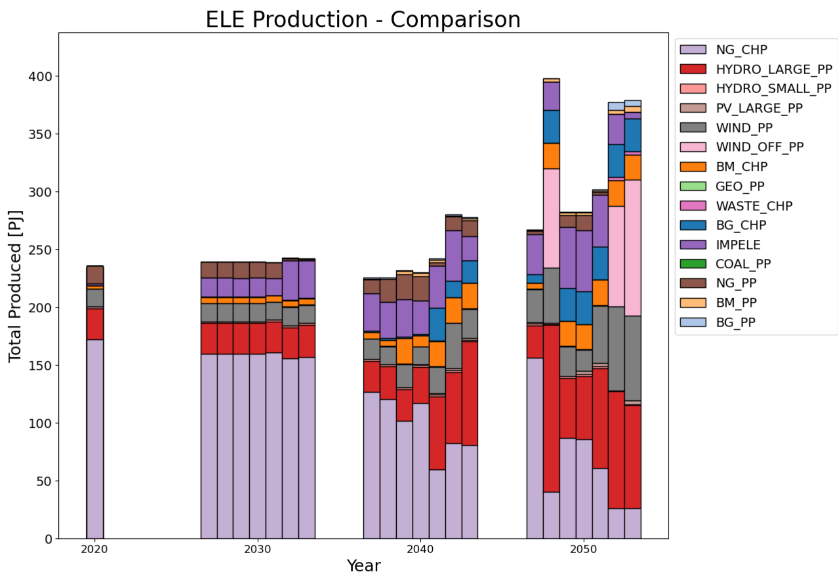

Figure 4.24: Comparison between all the scenarios for electricity production in the primary sector

In the first years of the planning horizon, the system's configuration is practically the same in all scenarios, but for the last year, three scenarios stand out from the others. These are the cases where limits on emissions and activities were established, which not only present a higher total electricity production, but also have a considerable share of it produced by offshore wind power plants. It is important to note that despite not having a big share on total electricity production, electricity imports have a significant reduction on the ActLimEle scenario, as would be expected, being substituted mostly by offshore wind power plants.

Different from the BAU scenarios, heat production cannot be associated to electricity production in all scenarios as figure 4.25 depicts. Heat production always encompasses production from natural gas cogeneration plants, while also including higher shares of biomass and biomethanes cogeneration plants. For the same three scenarios highlighted for electricity, solar thermal also has a contribution on producing centralised heat.

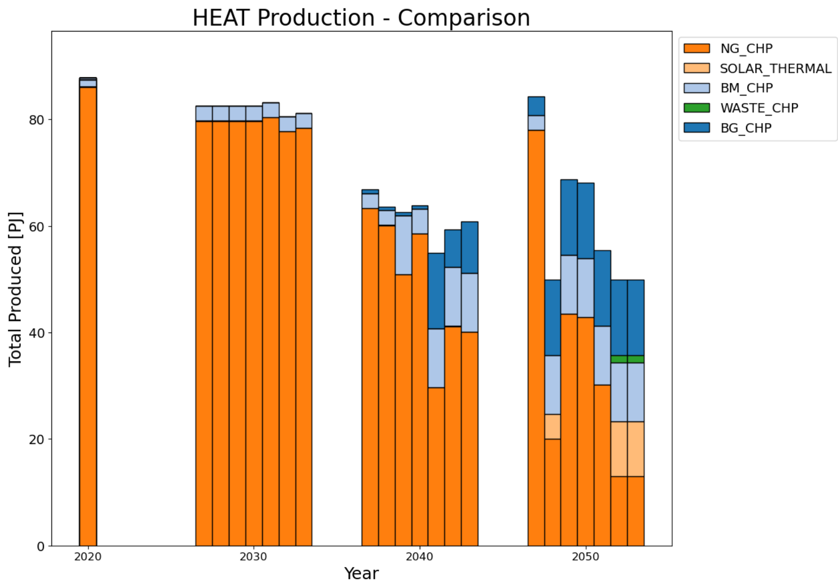

Figure 4.25: Comparison between all the scenarios for heat production in the primary sector

Hydrogen production divides the scenarios in two groups. As depicted in figure 4.26, hydrogen is initially produced mostly with natural gas steam reformers for all scenarios. However, in 2040 the scenarios present two distinct productions. While for the BAU and EmLim2050 scenarios, hydrogen production is still achieved through steam reformers, the other scenarios already present a big share of production through electrolysis processes, with the VeryHighCost2035 scenario standing out in total hydrogen production. For the year of 2050, all scenarios have almost all of the production through electrolysis processes, with the activity limits ones substituting natural gas steam reformers by biomass steam reformers.

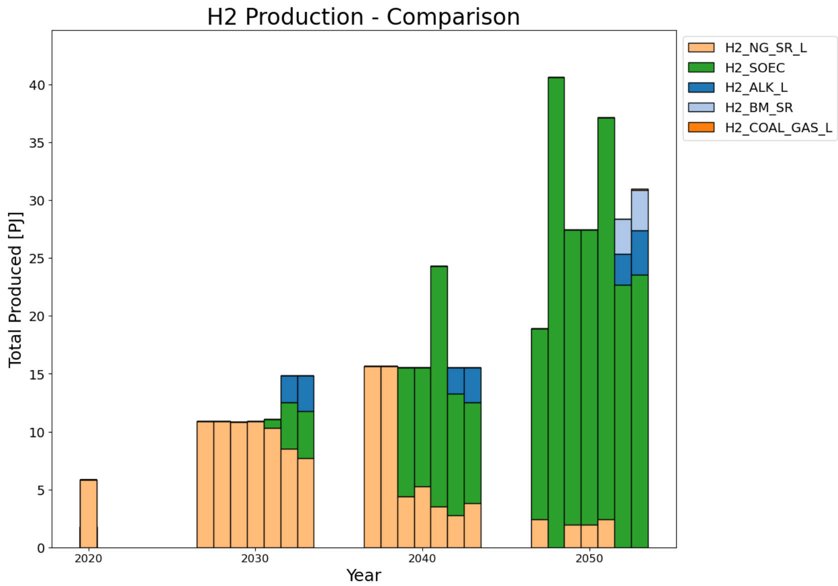

Figure 4.26: Comparison between all the scenarios for hydrogen production in the primary sector

Lastly on this sector, the production of oil products is again represented by diesel production. This production is presented in figure 4.27 and shows that, with the exception of the activity limits scenarios, the production in refineries is almost completely substituted by imports.

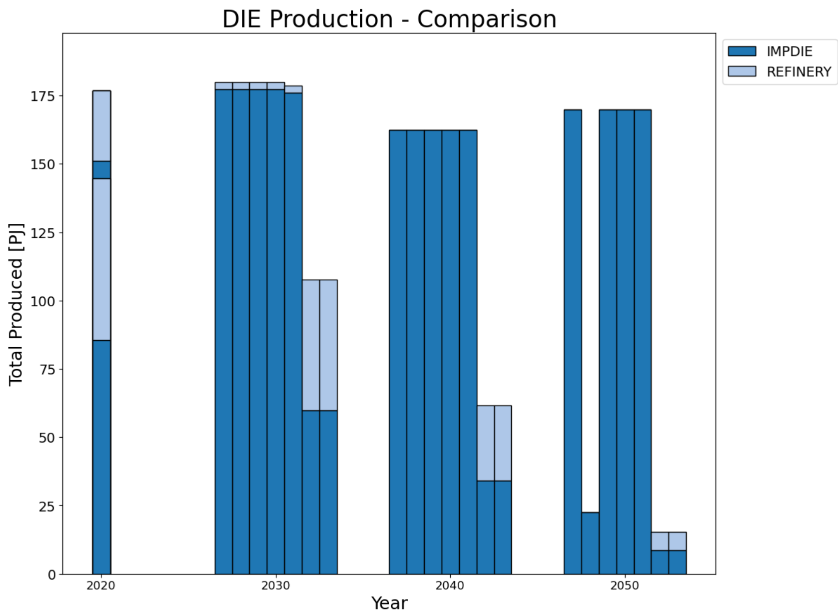

Figure 4.27: Comparison between all the scenarios for diesel production in the primary sector

The activity limits scenarios behave this way due to the limitation on diesel imports which may lead the model to produce via refineries to fulfill its demand. These last two scenarios, alongside with the emission limit one, present a significantly lower diesel production in the last year of analysis, while the rest stay equal to the BAU scenario. Note that due to recurring errors when generating this figure with the visualization tool aforementioned, the production for 2020 does not combine all the production from the refinery and the imports.

4.2.1.2 Residential buildings sector

The same approach followed in the primary sector is followed for this one. Starting with the evolution for dishwashing represented in figure 4.28. All the scenarios behave equally to the BAU scenario. Just as what was verified for this last scenario, all the alternative ones prioritise high efficiency technologies to the detriment of low efficiency ones. which also represents the evolution for clothes washing, refrigeration and lighting,

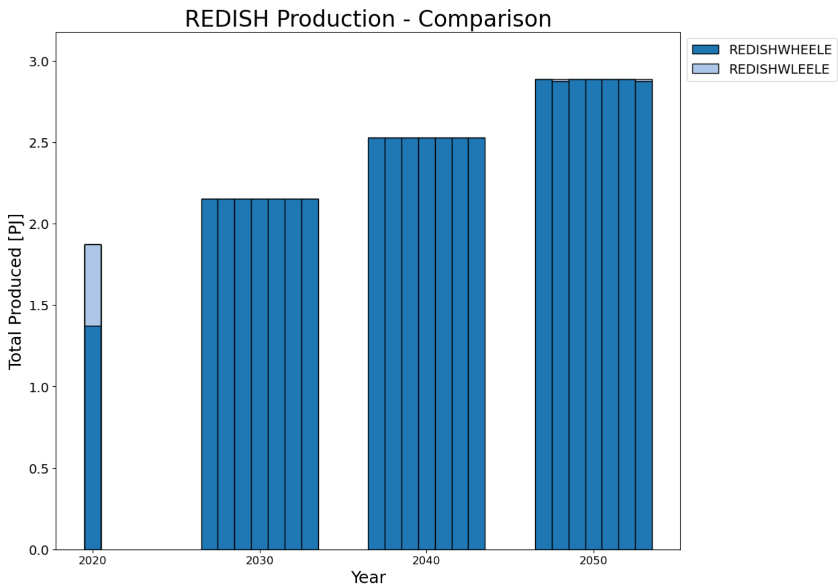

Figure 4.28: Comparison between all the scenarios for dishwashing production in the residential buildings sector

Despite having basically the same transitions for the alternative scenarios, water heating production evolves differently depending on the scenario, as it is depicted in figure 4.29. All scenarios initially substitute the capacity with biomass heaters. However, in the last years, thermoaccumulators become more prominent. The scenario with the highest share for these technology is the EmLim2050, which also presents a small share of biomass heater production. For the rest, small amounts are produced using technologies that rely on fossil fuels and on centralised heat.

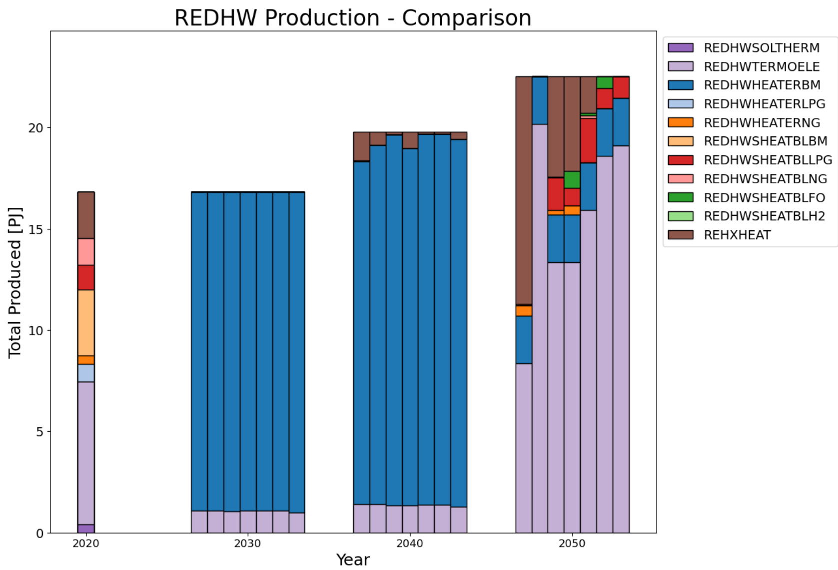

Figure 4.29: Comparison between all the scenarios for water heating production in the residential buildings sector

For the production of space heating, and as it is represented in figure 4.30, the same trend applies to all the scenarios: to produce this end-use with heat pumps. However, for 2040, the BAU and EmLim2050 scenarios do not have a contribution of this technology for the production as high as the other scenarios, still making use of fuel oil boilers. For all the scenarios there is a contribution from centralised heat and open fireplaces for the production, with these last one's disappearing after 2030. For the cooling production, the same trend of an increasing production through heat pumps is verified.

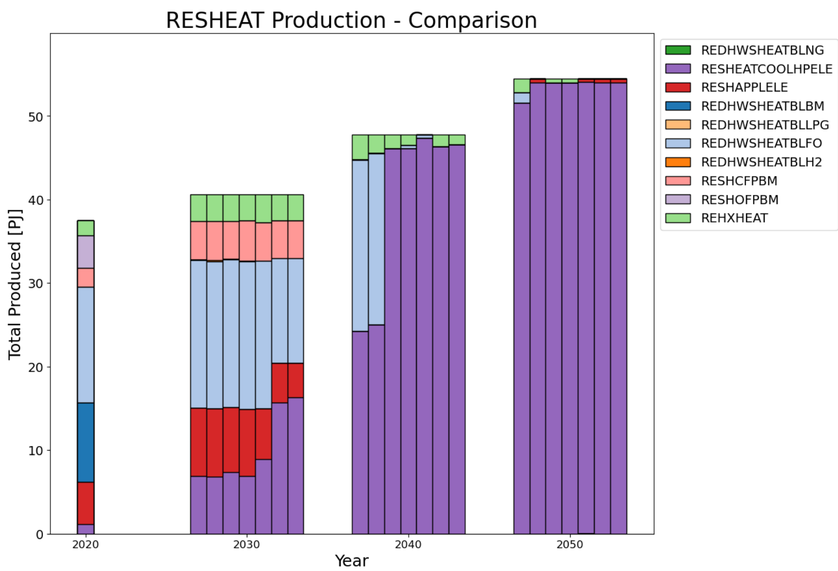

Figure 4.30: Comparison between all the scenarios for space heating production in the residential buildings sector

4.2.1.3 Services buildings sector

Just as for the BAU scenario, the services buildings sector shares trends for most end-uses with the residential buildings sector in all scenarios. For the end-uses satisfied only with electrical technologies, here represented by freezing production in figure 4.31, the pattern in all scenarios is the same as in the residential buildings sector: installing high efficiency technologies to substitute the low efficiency ones.

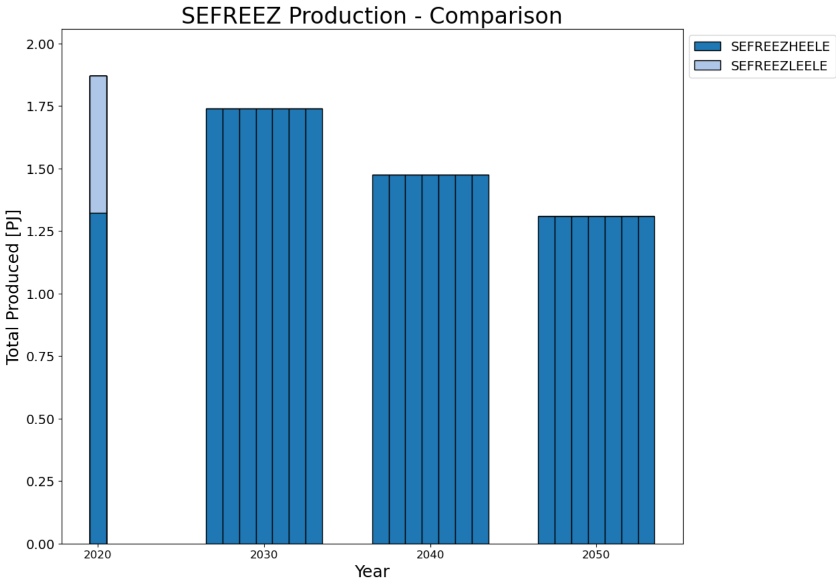

Figure 4.31: Comparison between all the scenarios for freezing production in the services buildings sector

Each bar represents one scenario, from left to right: BAU, EmLim2050, HighCost2035, HighCost2040, VeryHighCost2035, ActLim and ActLimEle. In the topic of water heating production, and similarly to the previous sector, the trend is to produce it recurring to thermoaccumulators.

However, a big difference is made evident in figure 4.32. For this sector, the production with thermoaccumulators has already a big contribution as early as 2020. The productions for the year of 2050 are very similar to the ones in the residential buildings sector. There is also a production in some scenarios of water heating making use of centrally produced heat, which are the scenarios where the production of heat and electricity in natural gas cogeneration plants is higher.

Figure 4.32: Comparison between all the scenarios for water heating production in the services buildings sector

With space cooling, the evolution of the installed technologies is similar to the BAU scenario. Instead of producing all that is necessary with heat pumps, the system also makes use of centralised air conditioners. As represented in figure 4.33, this behavior is equal to all the scenarios. This diversification might be explained from the equilibrium between the costs and efficiencies of these two technologies.

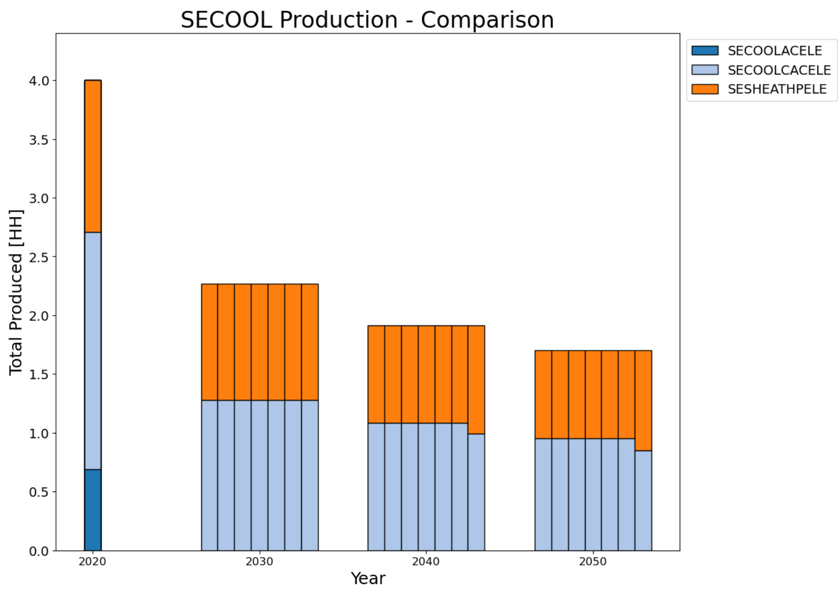

Figure 4.33: Comparison between all the scenarios for cooling production in the services buildings sector (PJ)

While heat pumps are more expensive, they also present a higher efficiency. With centralized air conditioners the opposite is verified, as it has lower costs but a lower efficiency too. As the system cannot determine an objective lower cost option, decides on keeping and installing both technologies proportionally to each other. When comparing with the results of other end-uses' production evolution, this was found to be an exception and, so, it is registered.

4.2.1.4 Industrial sector

Despite presenting different trends between different scenarios for some end-uses, for the production of process heat by boilers the scenarios evolve in very similar ways. As shown in figure 4.34, the system evolves in all scenarios towards a production with a major share from very high efficiency boilers, and a smaller one from very high efficiency boilers.

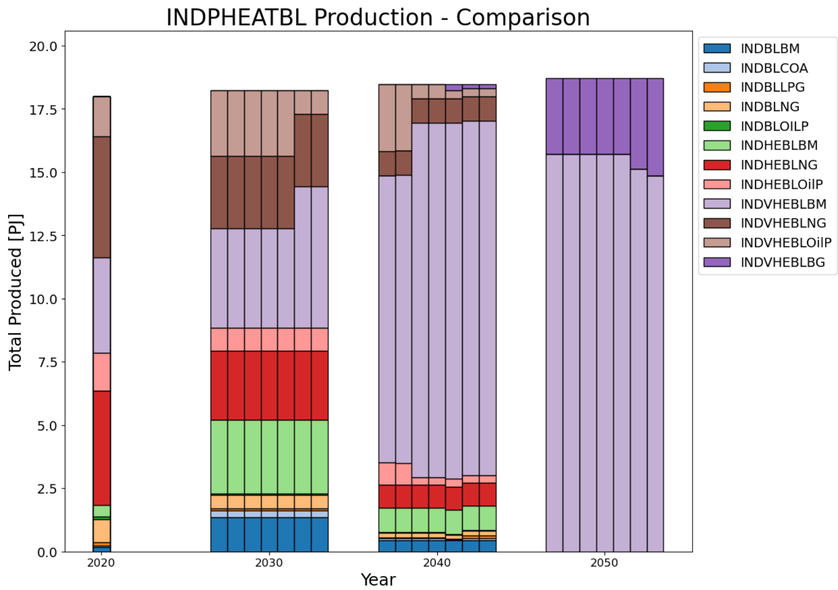

Figure 4.34: Comparison between all the scenarios for process heat production from boilers in the industrial sector

Each bar represents one scenario, from left to right: BAU, EmLim2050, HighCost2035, HighCost2040, VeryHighCost2035, ActLim and ActLimEle. For the intermediate years, the scenarios make only slightly different uses of the technologies with residual capacities. It is important to note also that before fully introducing very high efficiency biomass boilers, the system makes use of high efficiency boilers in all scenarios.

Still in the topic of similar evolutions, as figure 4.35 represents, the pulp production transitions from the technologies present on the residual capacity to biomethane fuelled ones for all scenarios. The same applies to the production of crude steel, aluminium, crude aluminium flat glass, hollow glass and ammonia. As the only alternative for the reduction of emissions and natural gas imports, biomethane assumes itself as the main driver for change in industry specific end-uses. This is due to the fact that biomethane presents a lower emission ratio when compared to natural gas, having impact on the fulfillment of the activity limits (as biomethane is not considered for these limits), the emissions limits and contributes to lower emissions penalties.

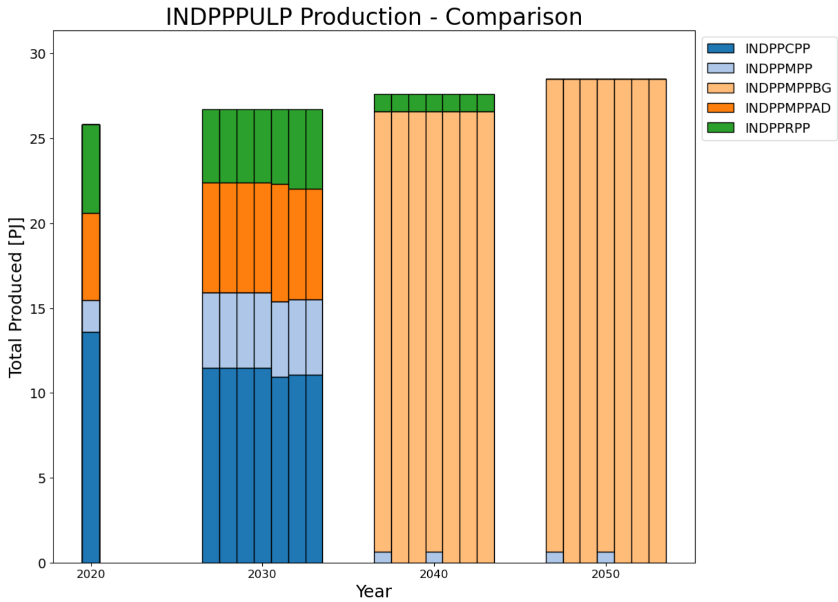

Figure 4.35: Comparison between all the scenarios for pulp production in the industrial sector

Lastly on the topic of similar evolutions between all scenarios, chlorine production evolution, depicted in figure 4.36, shows that the option for high efficiency technologies is the most logical one for the production of end-uses such as this one or lighting, just as what was verified for the residential and services buildings sectors. Once again, the option for higher efficiency technologies comes from the reduction of overall costs from the decrease on the use of the fuel.

Starting the topic of different evolutions between scenarios, steam production evolution shows how different the evolution for the energy system can be for the different conditions imposed in the scenarios, as it may be observed in figure 4.37. In the first years of the planning horizon, all the scenarios behave similarly. However, starting in 2040, big differences arise between the scenarios. For this year, while most of the scenarios transition to a production mainly based on coal steam boilers, the VeryHighCost2035 scenario evolves into assuring a production mostly based on hydrogen. In the last year of the time-frame of analysis, and accompanied by the emission limit scenario, the same VeryHighCost2035 scenario produces this end-use's production using hydrogen steam boilers with a share of approximately 80%, with the rest being produced by biomethane steam boilers. The other high carbon costs scenarios follow the same approach as the BAU one, while the activity limits scenarios obtain a compromise between the other two sets, with the production being almost equally distributed between coal, hydrogen and biomethane boilers. This evolution is also verified for the production of the HVAC, steel and process heat by boilers in the cement and lime industry.

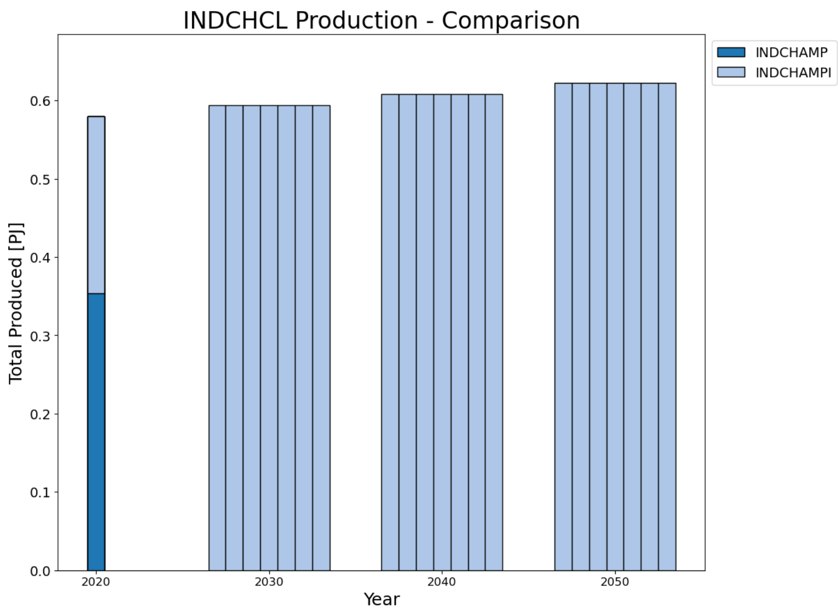

Figure 4.36: Comparison between all the scenarios for chlorine production in the industrial sector

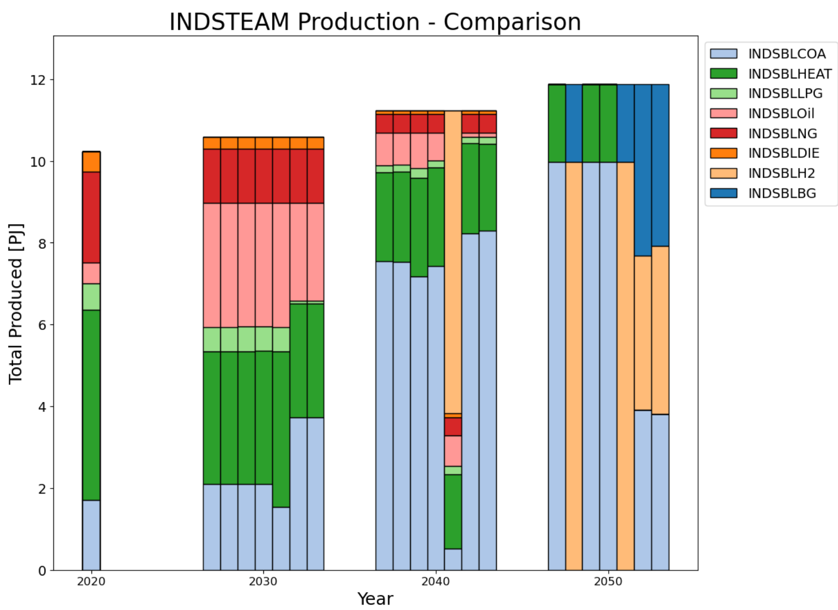

Figure 4.37: Comparison between all the scenarios for steam production in the industrial sector

Lastly on the industrial sector, the production of process heat by ovens also has different trends, as shown in figure 4.38. Despite having similar evolutions until the year of 2040, in the last year of analysis the configurations differ between scenarios.

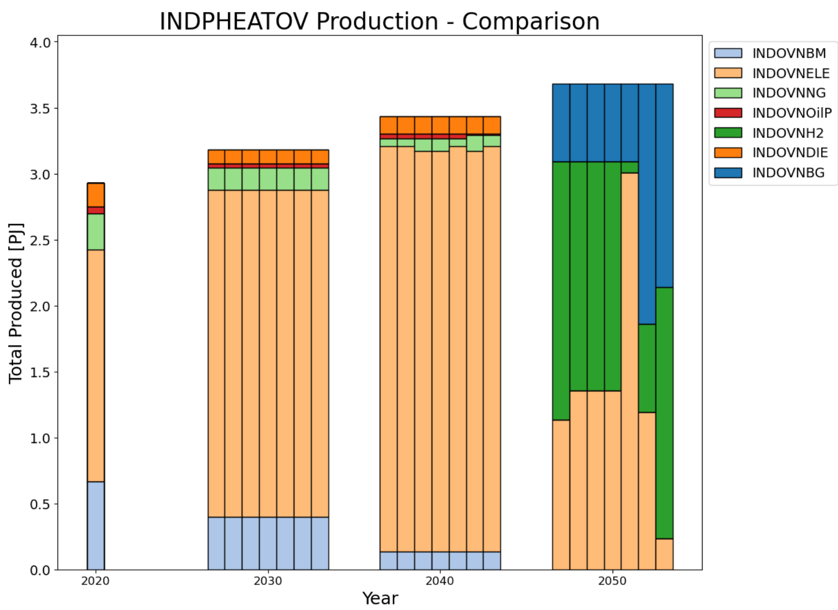

Figure 4.38: Comparison between all the scenarios for process heat production from ovens in the industrial sector

For the BAU, EmLim2050, HighCost2035 and HighCost2040 scenarios the characterization of the production is practically the same with hydrogen and electrical ovens producing 80% of the demand between them and the other 20% associated to biomethane ovens. The ActLim scenario presents the same production from electrical ovens as the BAU one, but the rest is only partially produced by hydrogen ovens, with a considerable share associated to biomethane ovens. In the VeryHighCost2035 scenario the production is assured almost entirely by electrical ovens, with a small share for biomethane and a residual one for hydrogen. The ActLimEle scenarios presents a production from hydrogen ovens similar to the one in BAU, but the smallest one from electrical ovens. One important detail is that this is the end-use where there is the biggest difference between the ActLim and the ActLimEle scenarios. The evolutions for process heat production by kilns are very similar to the ones on this end-use.

4.2.1.5 Transports sector

For the transports sector, the scenarios follow similar approaches to the one on the BAU scenario. The exception for this is the passenger road transport by car, which, as depicted in figure 4.39, can be separated into two groups: the ones that make a full transition for electrical solutions and the ones that do not. Each bar represents one scenario, from left to right: BAU, EmLim2050, HighCost2035, HighCost2040, VeryHighCost2035, ActLim and ActLimEle. For the scenarios that transition to electrical solutions, this transition starts as early as 2030, with the exception of the EmLim2050 scenario. The two scenarios that make this smooth transition are the activity limits ones. For the rest of the scenarios, the system does not abandon the solutions that make use of diesel, with them representing 100% of the production slightly after the year of 2030. The same is verified for the freight transport by light duty vehicles and freight aviation transport. However, for this last one, as happens in the BAU scenario, the system incorporates electrical solutions in the last years. This end-use is an example of the inefficiency of higher carbon costs in reducing the use of fossil fuels.

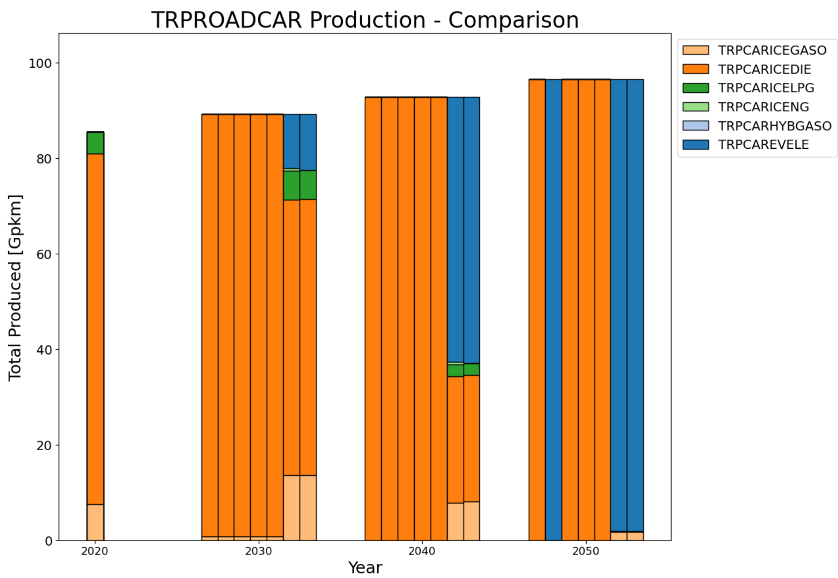

Figure 4.39: Comparison between all the scenarios for passenger road transportation by car in the transports sector

In the production of passenger road transport by 2 wheel vehicles, all the scenarios evolve to the same final state, as represented in figure 4.40. However, the activity limits scenarios take more time to transition from a full production by gasoline technologies to a fully electrical one. The evolution is the same for the production of passenger rail, passenger aviation and freight rail transport. For the production of road transport by bus, figure 4.41 shows that in all scenarios the system transitions into hydrogen using technologies.

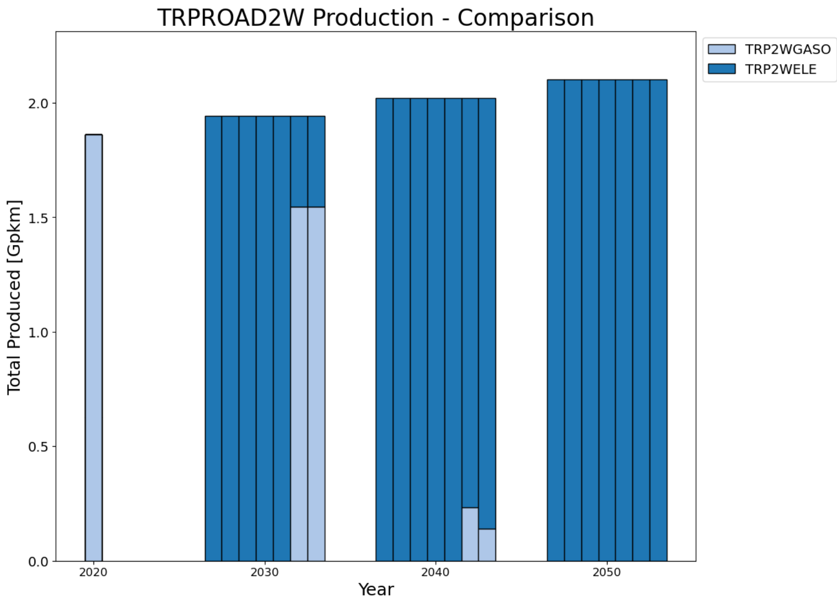

Figure 4.40: Comparison between all the scenarios for passenger road transportation by 2 wheels vehicles in the transports sector

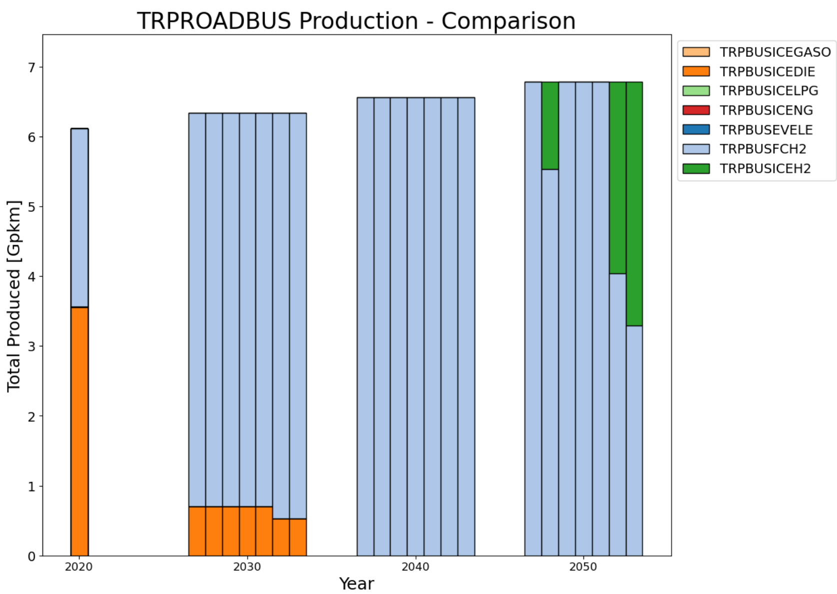

Figure 4.41: Comparison between all the scenarios for passenger road transportation by bus in the transports sector

The main difference relies in the technologies that the system chooses to produce the necessary demand. While in the BAU and high carbon costs scenarios the system only makes use of fuel cell vehicles, for the activity and emission limits ones, the system also resorts to hydrogen powered internal combustion engine vehicles, all this only for the last years. The same happens in the production of freight transport by heavy duty vehicles and freight shipping transport.

4.2.1.6 Agriculture sector

In this sector, the system makes the same choices for all scenarios and in all the end-uses, which is an indicator that, for this sector, the cost-efficient evolution is practically the same as for the one that reaches certain targets of decarbonisation and/or self-sufficiency. Figure 4.42 shows just that, as in the production of heat the system always abandons the technologies in the residual capacity as early as possible, transitioning into a practically full production that resorts to hydrogen. The evolution of the production of machinery and irrigation is also equal to the one in the BAU scenario.

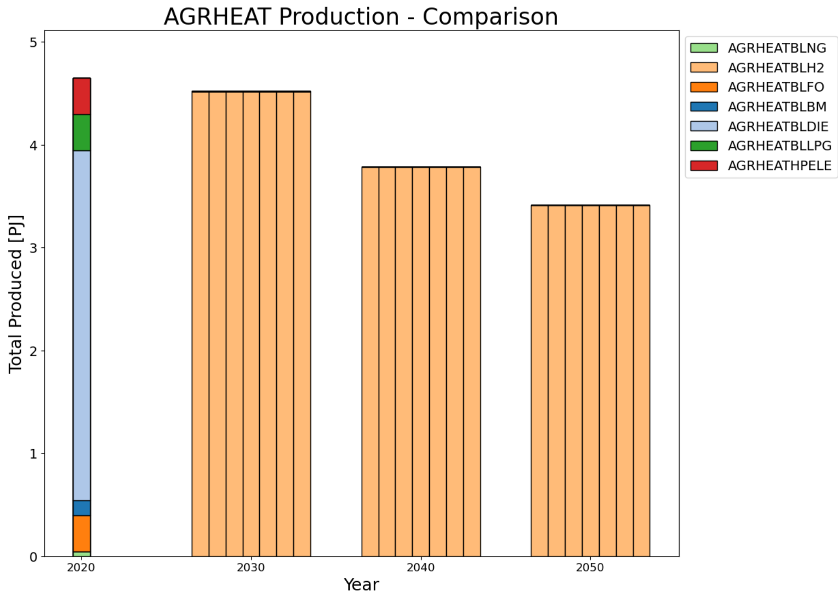

Figure 4.42: Comparison between all the scenarios for heat production in the agriculture sector

4.2.2 Emissions

After characterizing how each scenario evolves its installed capacities and production between all the technologies, the need for comparing their emissions arises. The total annual emissions evolution for each scenario is represented in figure 4.43, which provides insightful information on the effect of the modifications introduced in the model. While all the scenarios achieve a final annual emissions value lower than the one on the BAU scenario, some are able to comply with the targets for emission reductions and others are not. EmLim2050, ActLim and ActLimEle are the ones that comply with the goals, with these last two being able to do so in a more smooth way, as the first abruptly decays only in the last year. The scenarios that stay further away from the objective are the high carbon cost ones, whilst for VeryHighCost2035 an intermediate level is reached, however still far from what would be desired.

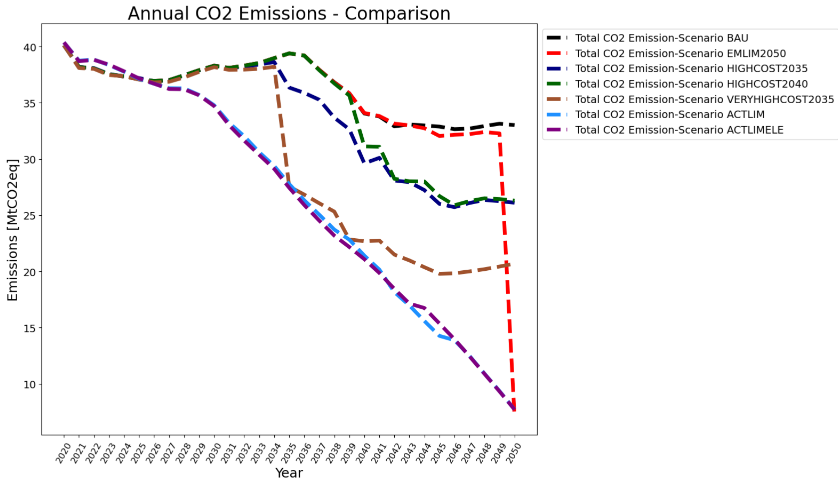

Figure 4.43: Comparison between all the scenarios for the annual emissions evolution

In order to understand what contributes to each scenarios emissions, figure 4.44 represents the share of each primary resource in the total emissions.

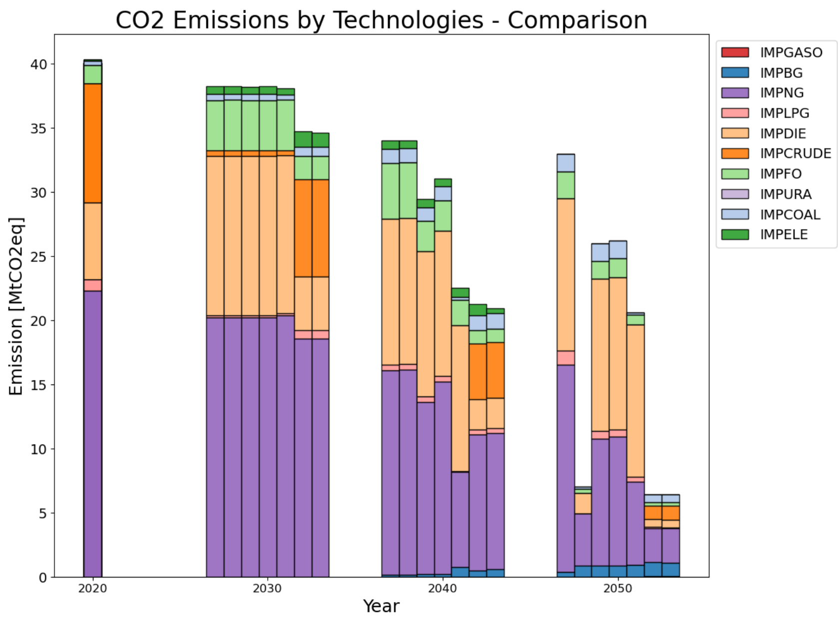

Figure 4.44: Comparison between all the scenarios for the technologies' shares in the emissions

Each bar represents one scenario, from left to right: BAU, EmLim2050, HighCost2035, HighCost2040, VeryHighCost2035, ActLim and ActLimEle. Apart from the activity limits scenarios, there is a general trend to substitute the import of crude by the import of the already refined oil products, with diesel and fuel oil being the more representative ones. The figure also makes evident that the scenarios that were able to reduce the most its emissions were the ones for which the contributions of natural gas and diesel imports were heavily reduced.

4.2.3 Costs

Despite being able to have a considerable impact on the environment, policies aiming for the reduction of emissions have to consider the effects that those measures may have on the end-users' costs of energy. For that, a comparison of the total costs for all the scenarios needs to be carried out. This comparison may be visualized in the following figure 4.45. Despite all scenarios presenting similar costs throughout the planning horizon, there are three that exceed the values of the others. They are the ones that impose activity and emission limits on the system, with EmLim presenting a final annual cost much higher than the other ones. The rest of the scenarios present very similar costs throughout the time-frame of analysis.

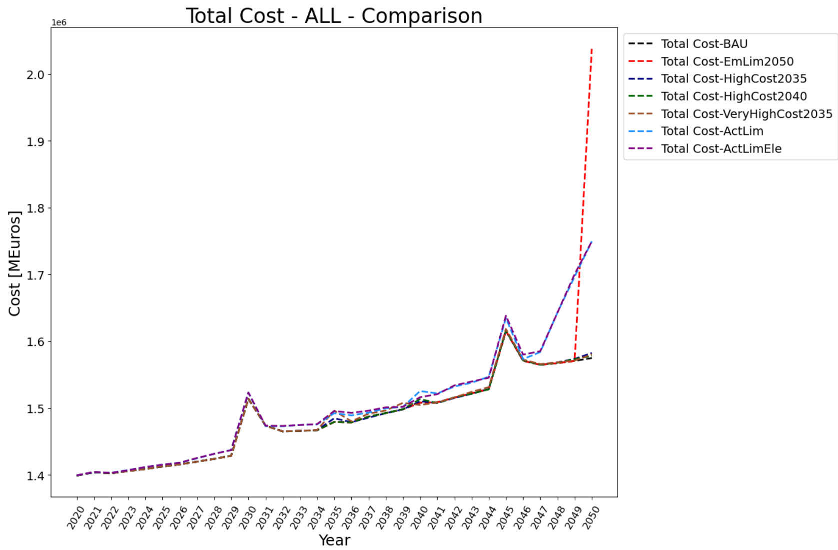

Figure 4.45: Comparison between all the scenarios for the total costs

4.2.4 Imports

Finally, it is time to establish a comparison on imports values for each one of the scenarios, and evaluate if the applied modifications for each one of them have any implications on future imports values. Figure 4.46 depicts the evolution of the total value of imports for each scenario. The ones that more successfully reduce the imports are the emission and activity limits scenarios, achieving a reduction of around 67% in the comparison with the imports on 2015, and of 54% when comparing to the BAU emissions in 2050. Intermediately, the scenario VeryHighCost2035 is able to achieve an emission reduction of 40% relative to 2015 values, and of 17% for 2050

BAU's emission. Despite reducing imports when comparing to 2015, the other two scenarios were not able to present a solution with a final level of imports lower that the one in BAU.

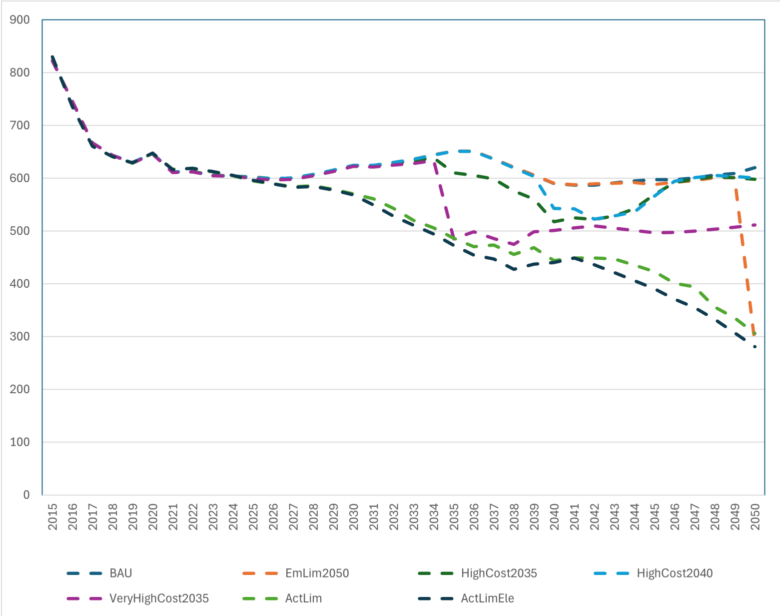

Figure 4.46: Comparison between all the scenarios for the total imports evolution (PJ)

To better understand in what way the scenarios were able (or not) to reduce their imports, figure 4.47 shows the evolution of the share of each imports technology in the total imports for each one of the scenarios.

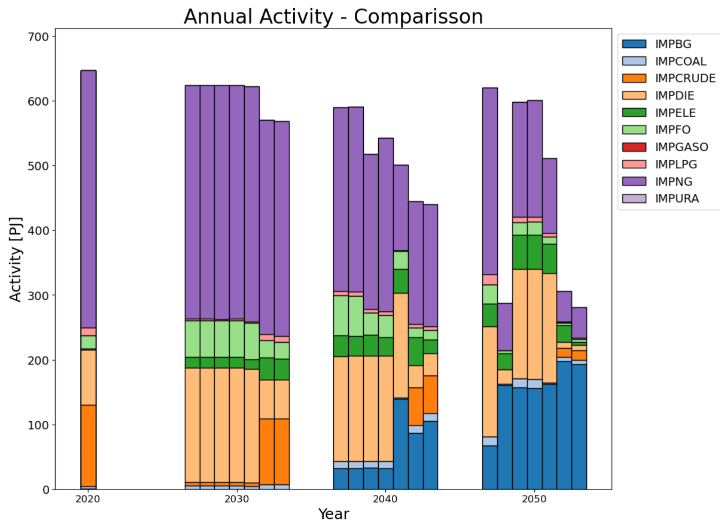

Figure 4.47: Comparison between all the scenarios for the imports technologies' share in the imports activity

Each bar represents one scenario, from left to right: BAU, EmLim2050, HighCost2035, HighCost2040, VeryHighCost2035, ActLim and ActLimEle. It shows that for the scenarios with the highest imports reduction the big changes are in the imports of natural gas and diesel, in line with what was observed for the emissions. The only technologies that increase their import values are electricity (with the exception of ActLimEle scenario) and biomethane which is set as the main replacement of natural gas in the energy system. If the biomethane imports were not considered, the limits scenarios would present an even higher imports reduction.

4.3 Results Overview

To facilitate a more comprehensive comparison of the overall performance across each scenario, the following Table 4.1 presents a division of the scenarios into groups when taking into account costs, emissions and imports on the last year. These groups combines scenarios that presented similar results for each category. The table states lowest for the scenarios with the lowest values in the specific category, highest for the ones with the highest values and intermediate for the ones in between. BAU sets the reference for low total costs, but also for high emissions and imports values.

Table 4.1: Groups for the performance indicators of each scenario

Scenario	**Costs group**	**Emissions group**	**Final imports group**
BAU	Lowest	Highest	Highest
EmLim2050	Highest	Lowest	Lowest
HighCost2035	Lowest	Upper Intermediate	Highest
HighCost2040	Lowest	Upper Intermediate	Highest
VeryHighCost2035	Lowest	Lower Intermediate	Intermediate
ActLim	Intermediate	Lowest	Lowest
ActLimEle	Intermediate	Lowest	Lowest

While presenting the lowest emissions and imports, the EmLim2050 scenario is the most costly one. Contrary to their denomination, HighCost2035 and HighCost2040 scenarios presented practically the same overall results. Despite being in the lowest cost group, these scenarios showed insufficient results on the reduction of emissions and even more on the reduction of imports, which was practically null when comparing to the ones on BAU. VeryHighCost, on the other side, was able to provided with optimised results when comparing to the high carbon costs ones'. Also in the group of lowest costs, it was able to approximate its emissions to the values on the limits scenarios, despite still being far. Imports were also reduced in this scenario, but are still far from what was achieved in the limits ones. Not as costly as the emission limit scenario, the activity limits scenarios still reach low values of emissions (and in a more organic way, not abruptly) and imports. These results also show the relationship between the reduction of emissions and the reduction of imports.

The reduction of imports is also related to the characterization of the system in a final energy consumption level and the specific carriers of use. For the scenarios that were not able to reduce the imports significantly, the end-use sectors did not abandon technologies that make use of fossil fuels, also contributing to a lower reduction on emissions. In the scenarios that effectively reduced the imports, the system invested in biomethane, hydrogen and an even higher share of electricity technologies in the end-uses sectors. Note that system evolved in the direction of producing electricity predominantly produced with endogenous resources, such as renewable energy resources and biomass.

When combined, the scenarios' results indicate that the paths that should be followed for reaching self-sufficiency in the Portuguese energy system are the same as for reaching carbon neutrality, with the main drivers for change being electricity, hydrogen and biomethane.

Chapter 5

Conclusions and future work

5.1 Conclusions

The central objective of this thesis was to assess the possible paths for self-sufficient Portuguese energy system. In order to accomplish this objective, a model representing the energy system was developed alongside with scenarios where small variations were introduced in the model.

This leads to a secondary goal which was to develop an open-sourced and fully disaggregated model. This was achieved with the completion of the representation of the agriculture sector and its connection to the primary one. One of the outcomes of this thesis is, consequently, a model that fully describes the energy sector and its energy intensive end-use sectors.

However, the primary outcome is a prooved relationship between self-sufficiency and emissions reduction for the Portuguese case. As Portugal does not produce fossil primary resources, they have to be imported. With this condition, it is proved that by controlling the imports, one result would be the reduction of the emissions.

The results from the scenarios comparison also show that the main drivers for reaching self-sufficiency (and consequently the emissions) are hydrogen and electricity, with this last one being mostly produced using endogenous resources such as renewable sources or biomass, and hydrogen produced via electrolysis. Biomethane will also be important for the reduction of emissions and for imports, if it is endogenously produced.

Lastly, increasing carbon costs may have an impact on both the imports and emissions. However, as it was shown by the scenarios' results, these emission penalties need to have very large values (at least five times greater than it is projected to be) to start decreasing imports and emissions in significant values. For the not so high costs' scenarios, the difference almost goes unnoticed.

5.2 Model limitations and future work

Despite having their demands fully corrected, no revision on the residual capacities for the residential and services buildings sectors was carried out. The industrial and transports sector did not have their demands revised and consequently the same for residual capacity.

As there are always room for improvement, there is also room for further research. From that, the following ideas can turn out to be of interest for future studies:

- Consider the integration of storage capabilities on the model, such as a connection of storage systems to renewable energy sources, or technologies such as pumped hydrological power plants;
- Further review the technologies and their techno-economic parameters, specially the end-use sector ones;
- Further describe carbon capture and storage technologies and their production chain;
- Study how useful can OSeMOSYS be on very small local communities scale, assessing the establishment of Positive Energy Districts.

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Appendix A

Diagram representing the energy system

This appendix provides a diagram that depicts the model used in this study. Note that for the industrial sector there is a representation of several technologies and demands that repeat themselves between the industries. Due to computational limitations, these repeating technologies and demands were condensed in the actual model.

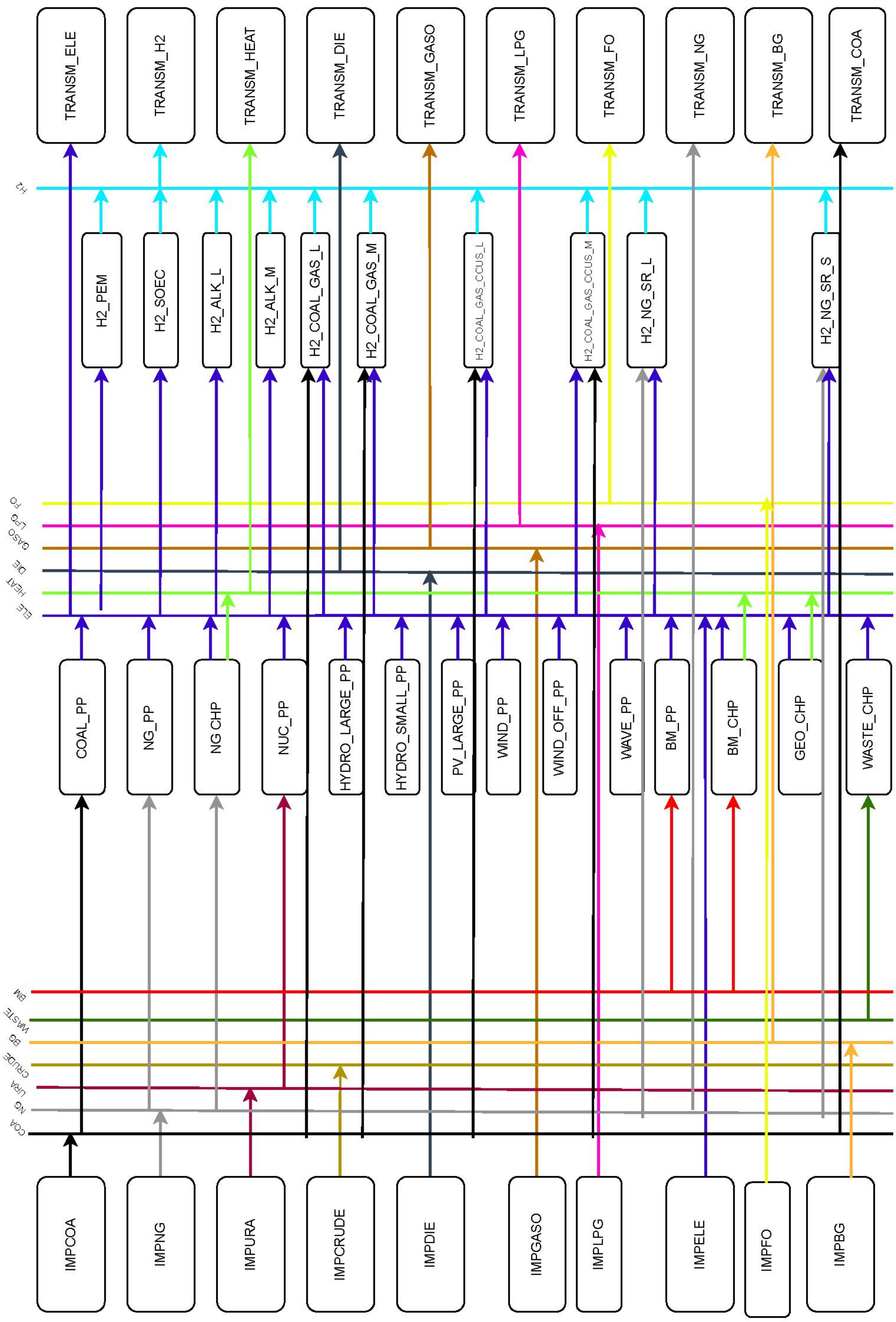

Figure A.1: Primary sector (part 1)

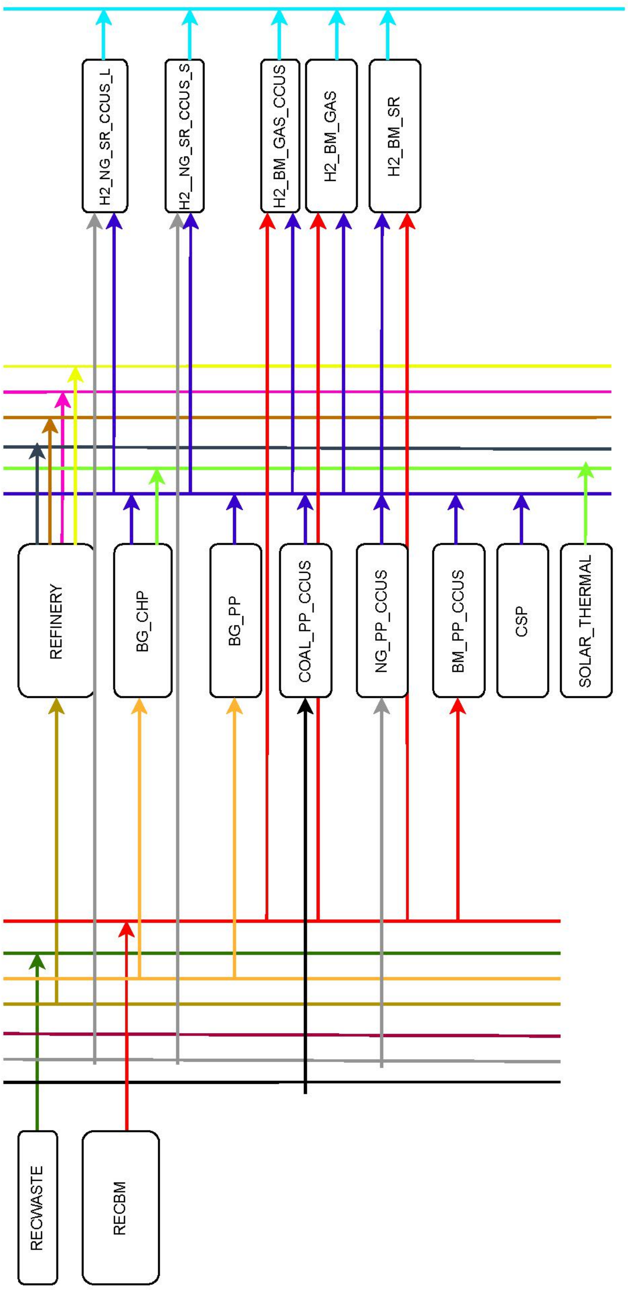

Figure A.2: Primary sector (part 2)

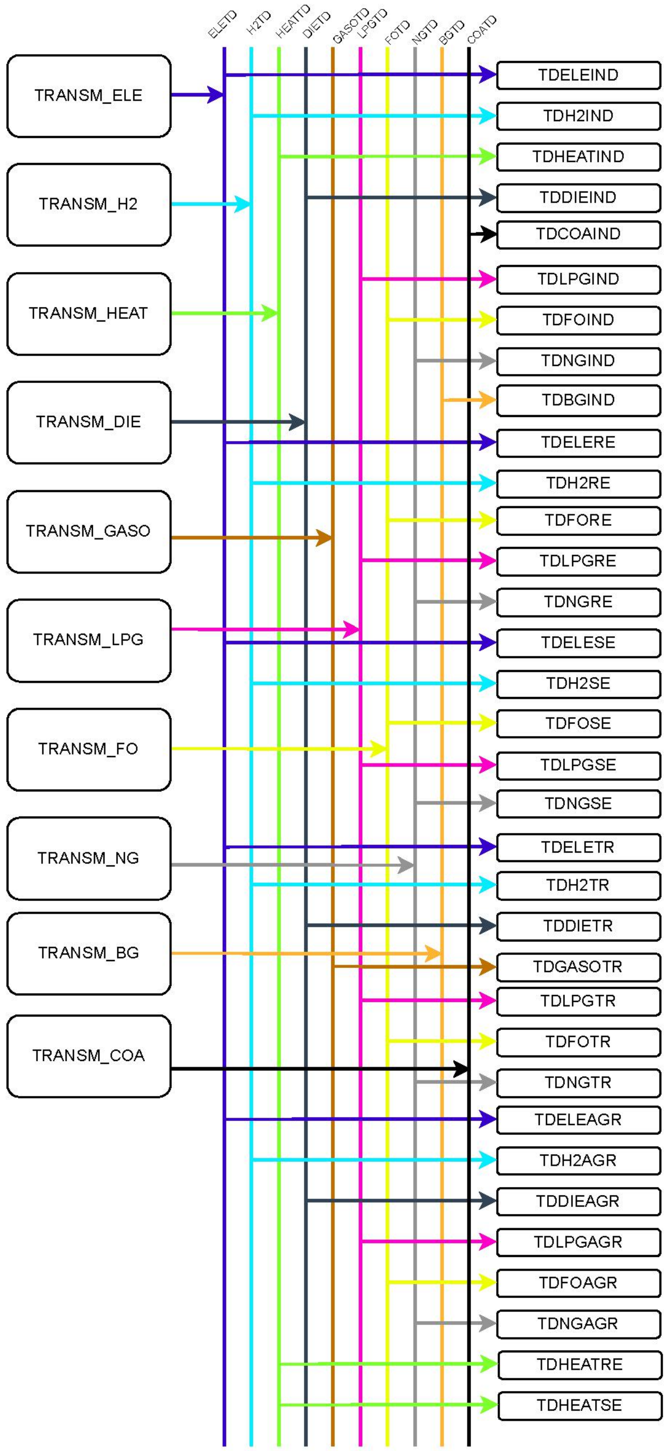

Figure A.3: Transmission and distribution

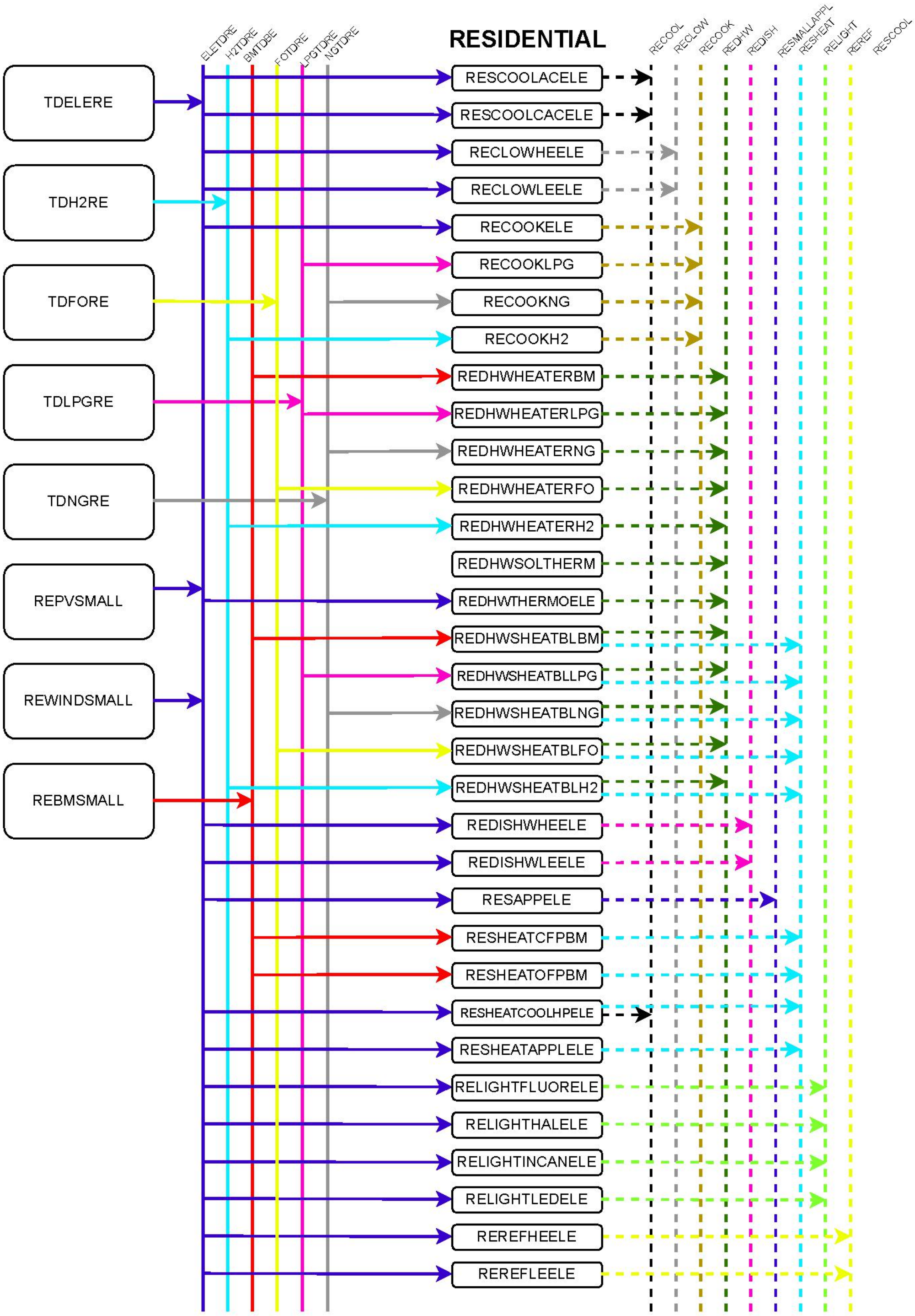

Figure A.4: Residential buildings sector

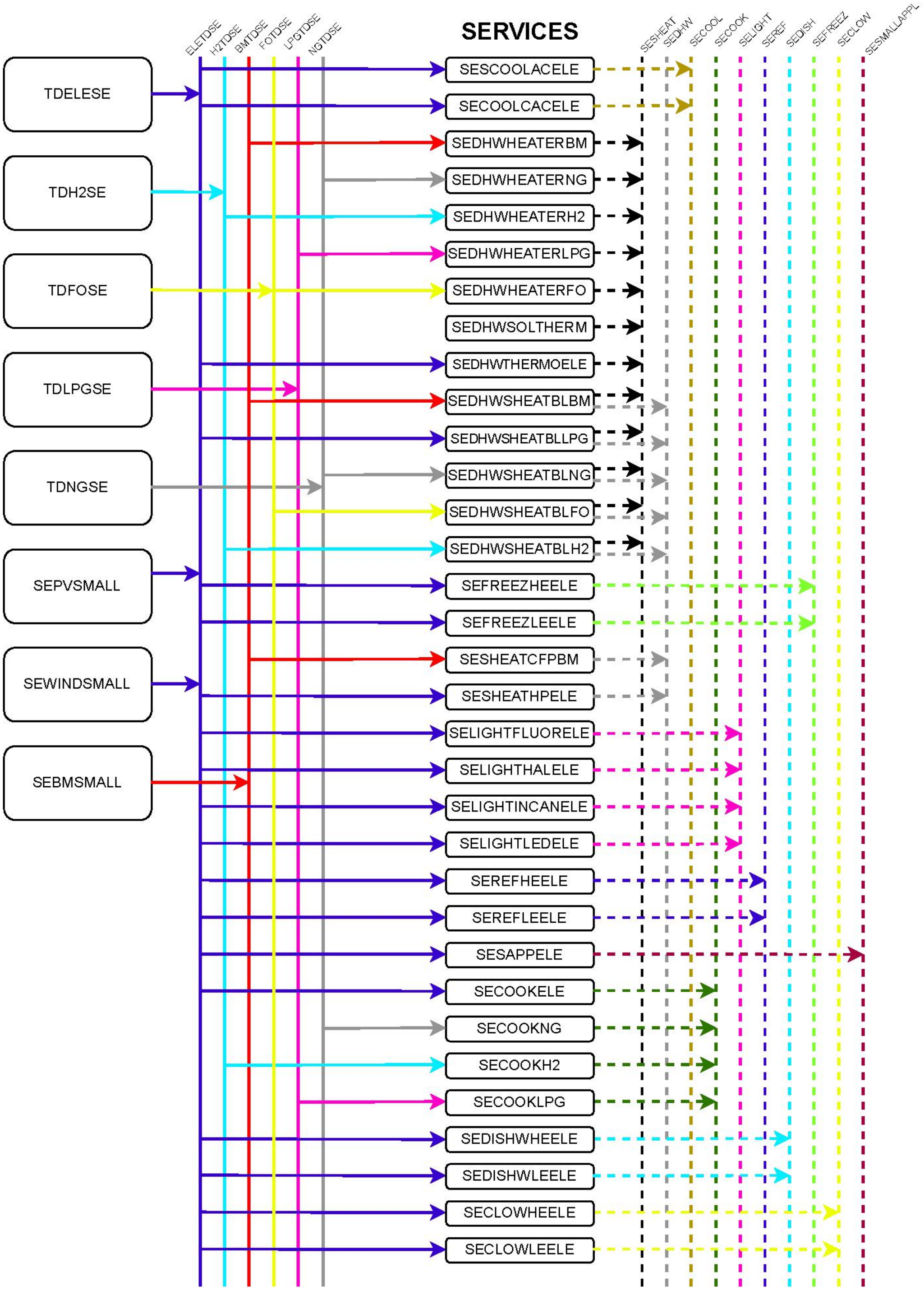

Figure A.5: Services buildings sector

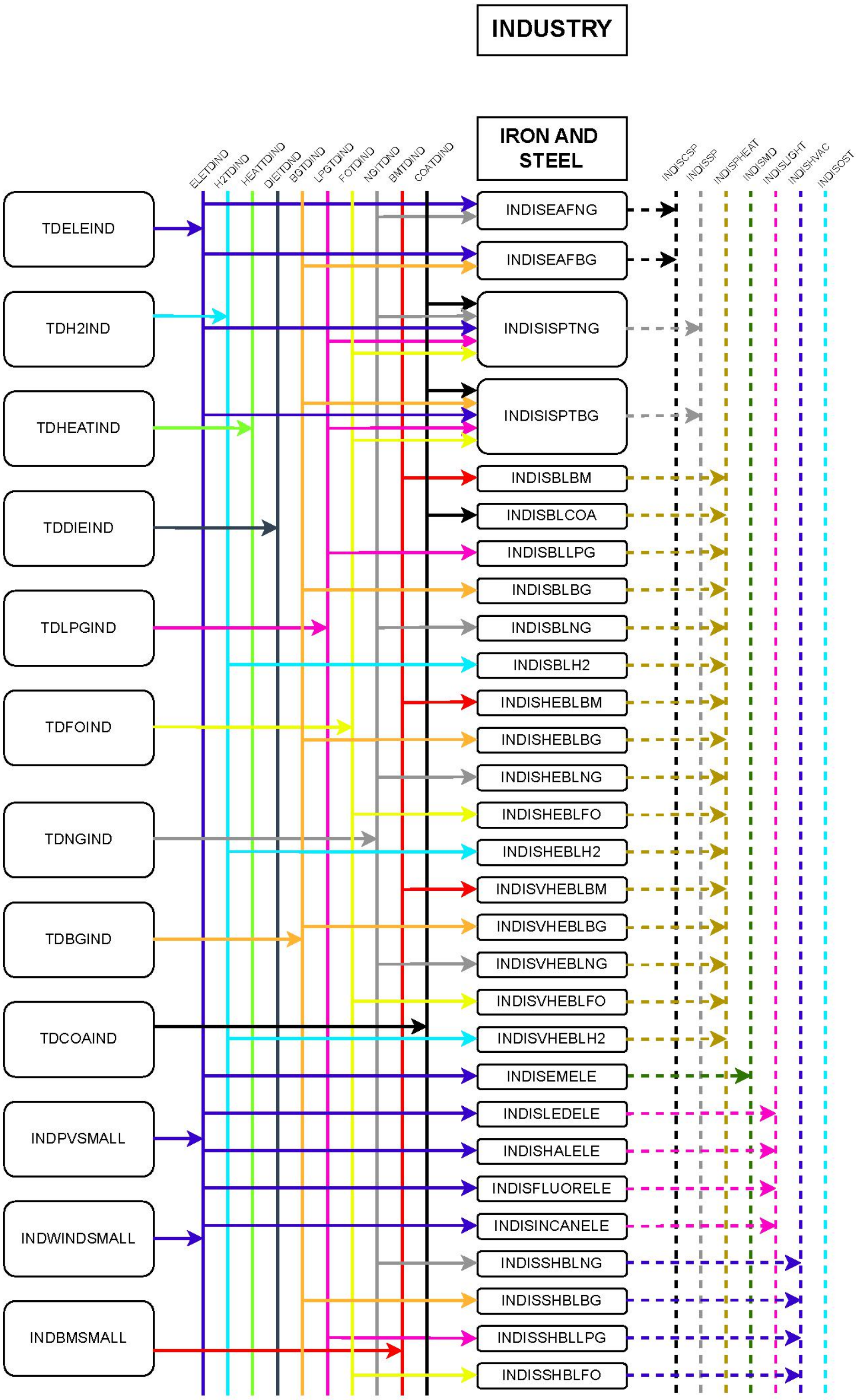

Figure A.6: Industrial sector (part 1)

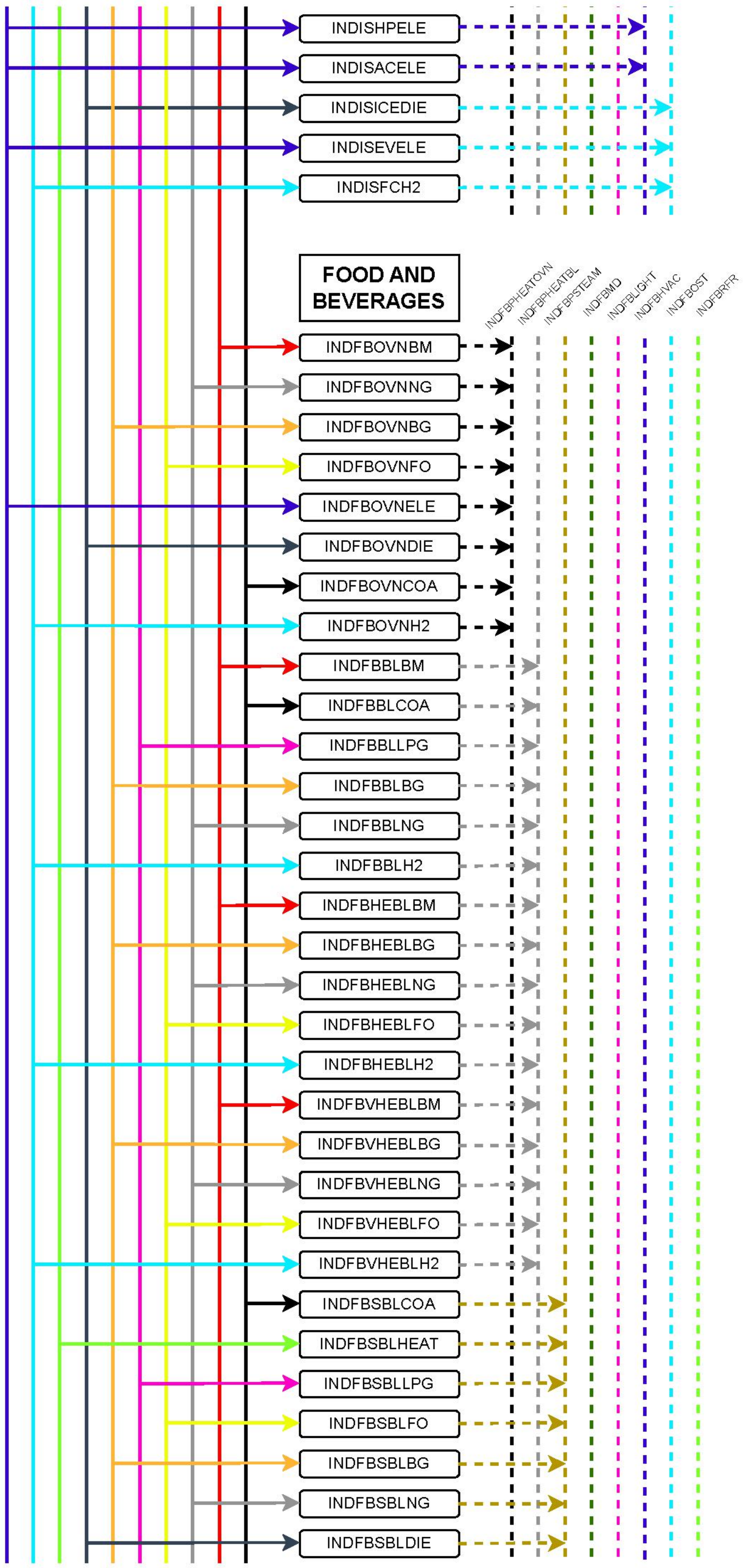

Figure A.7: Industrial sector (part 2)

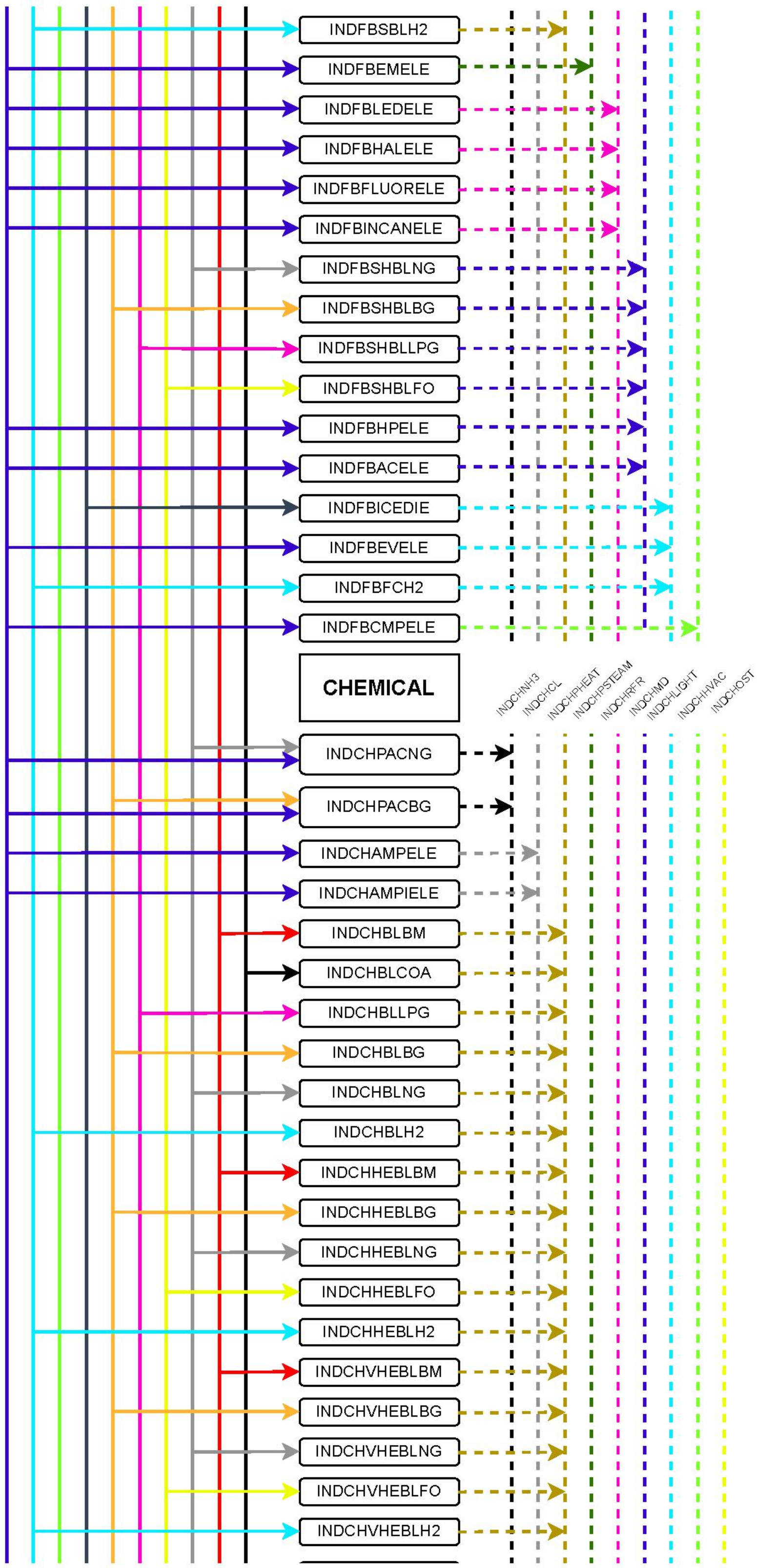

Figure A.8: Industrial sector (part 3)

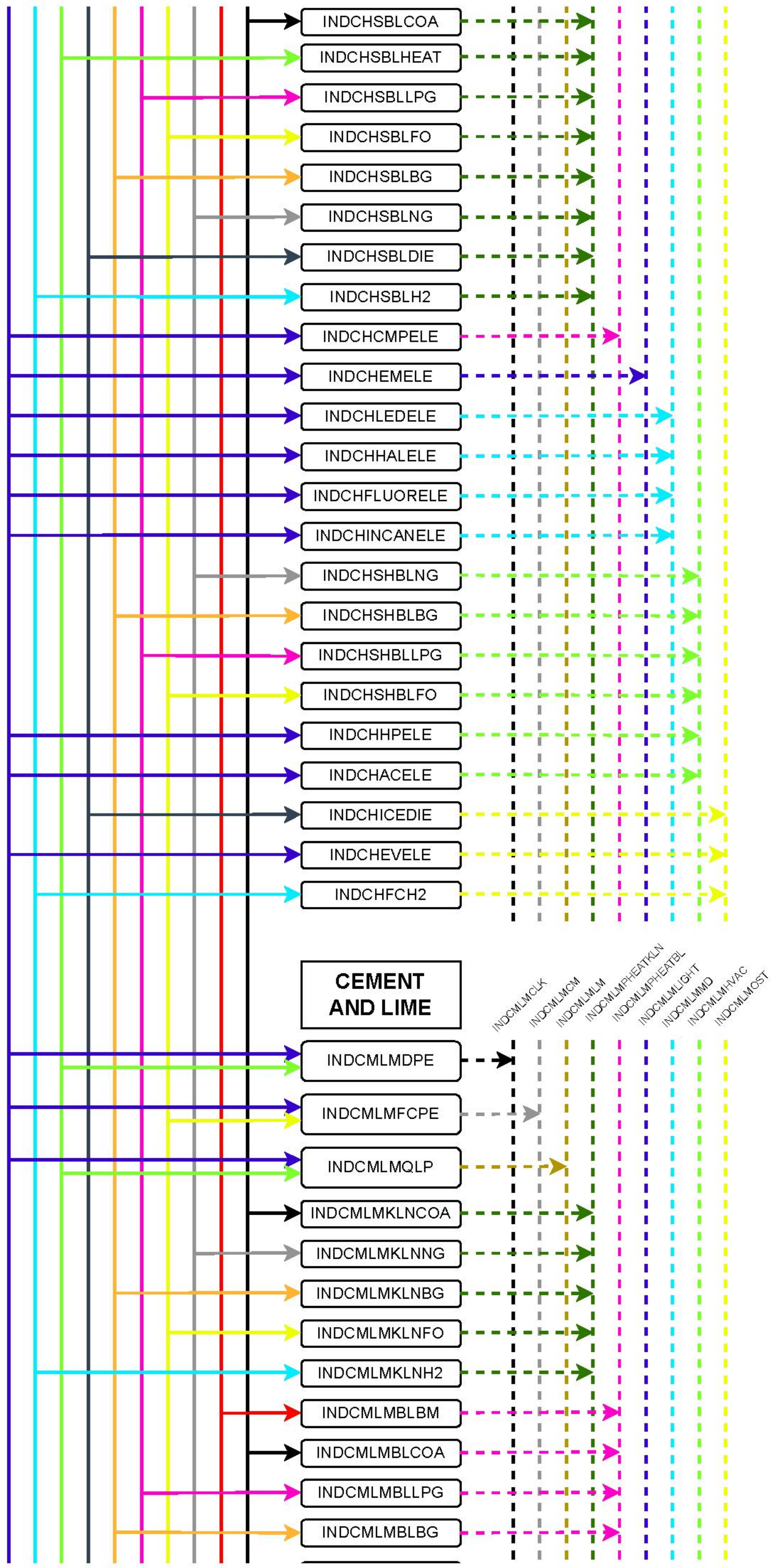

Figure A.9: Industrial sector (part 4)

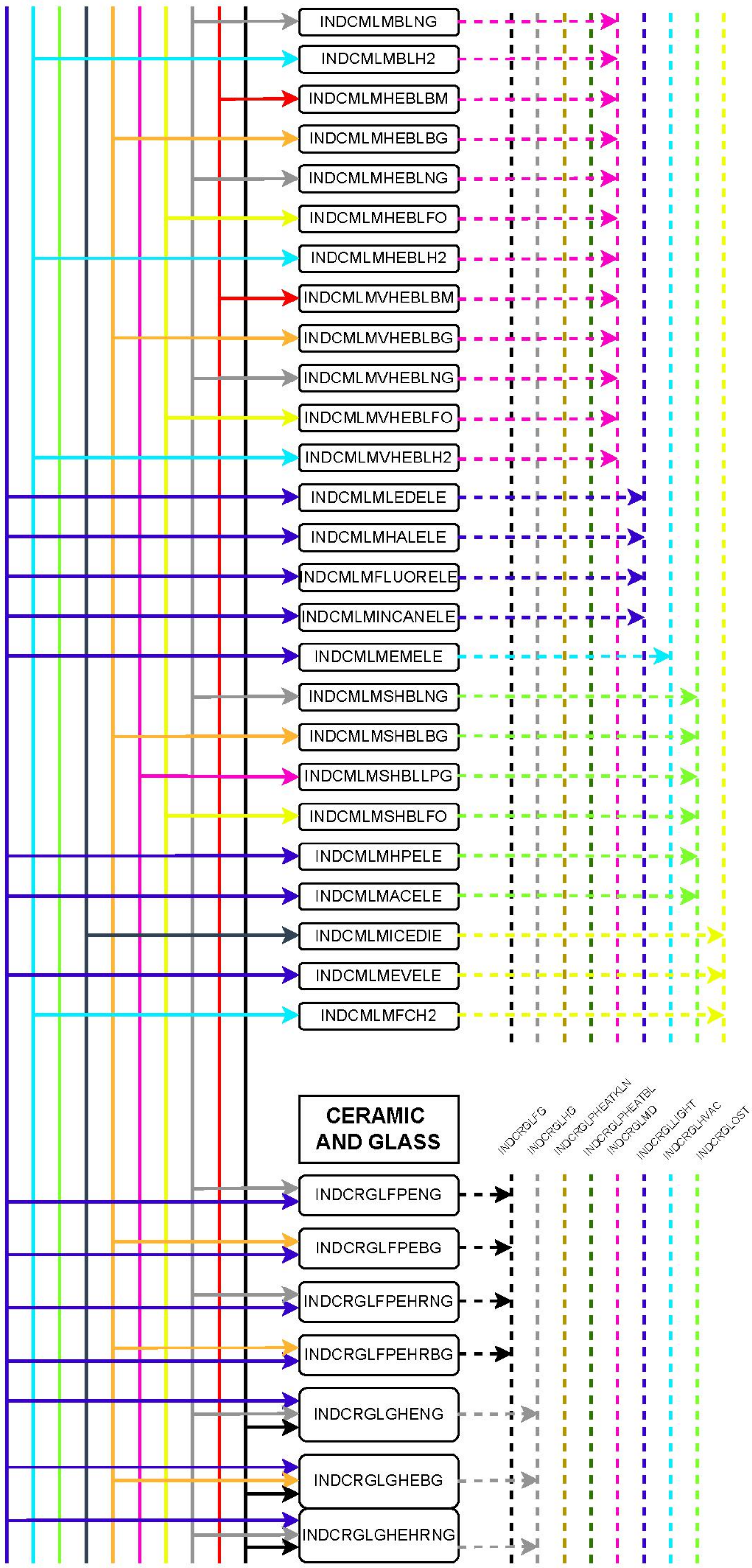

Figure A.10: Industrial sector (part 5)

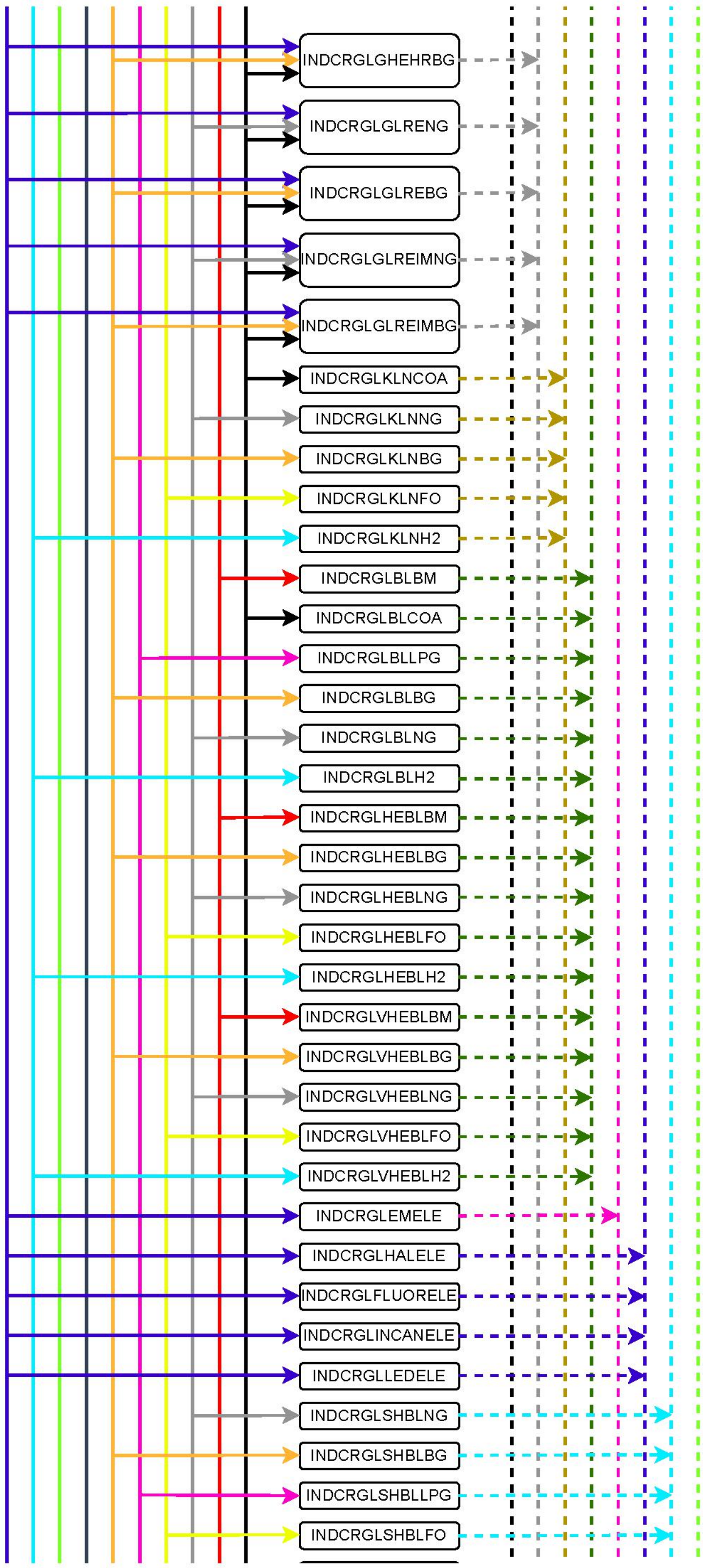

Figure A.11: Industrial sector (part 6)

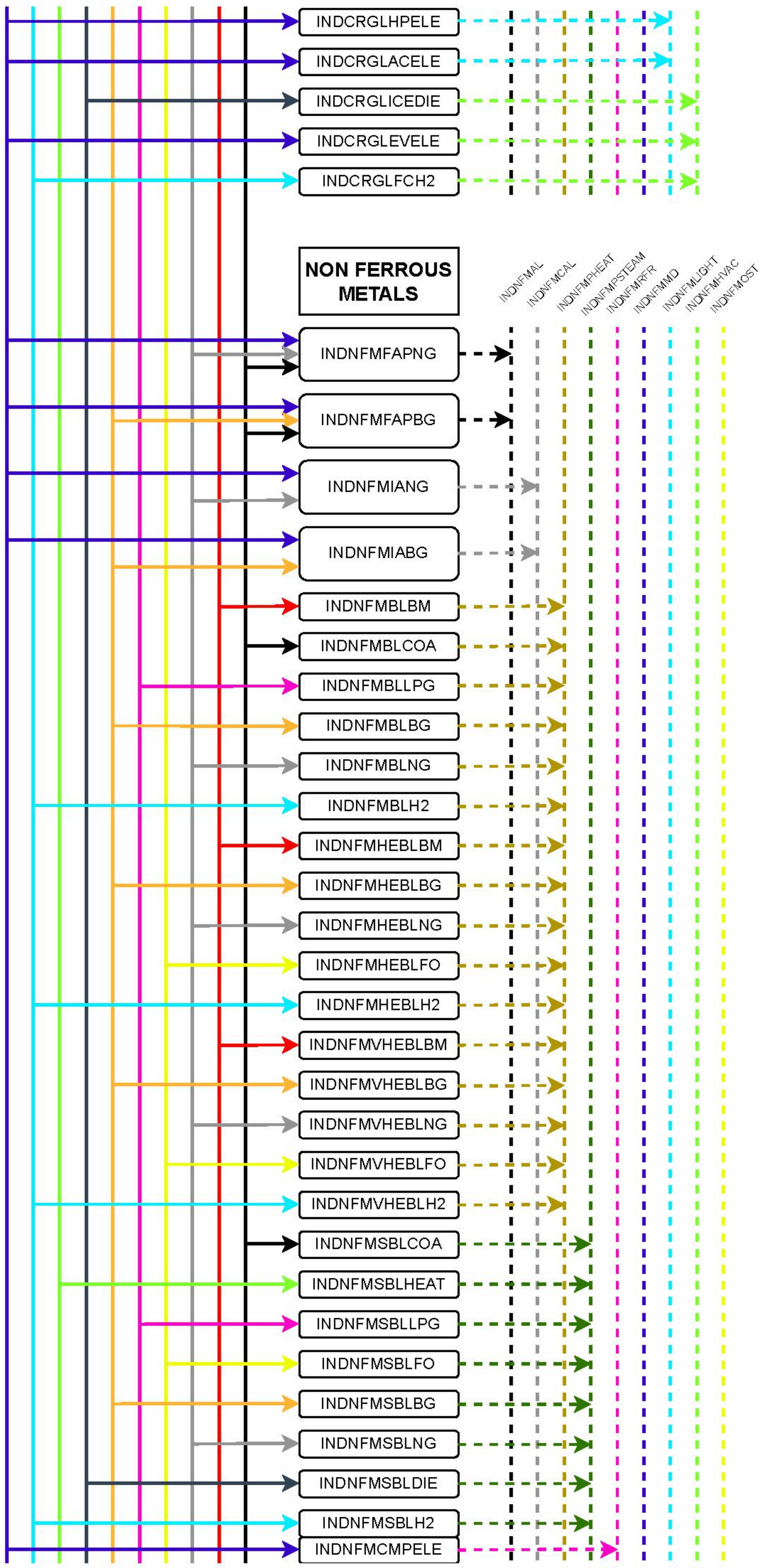

Figure A.12: Industrial sector (part 7)

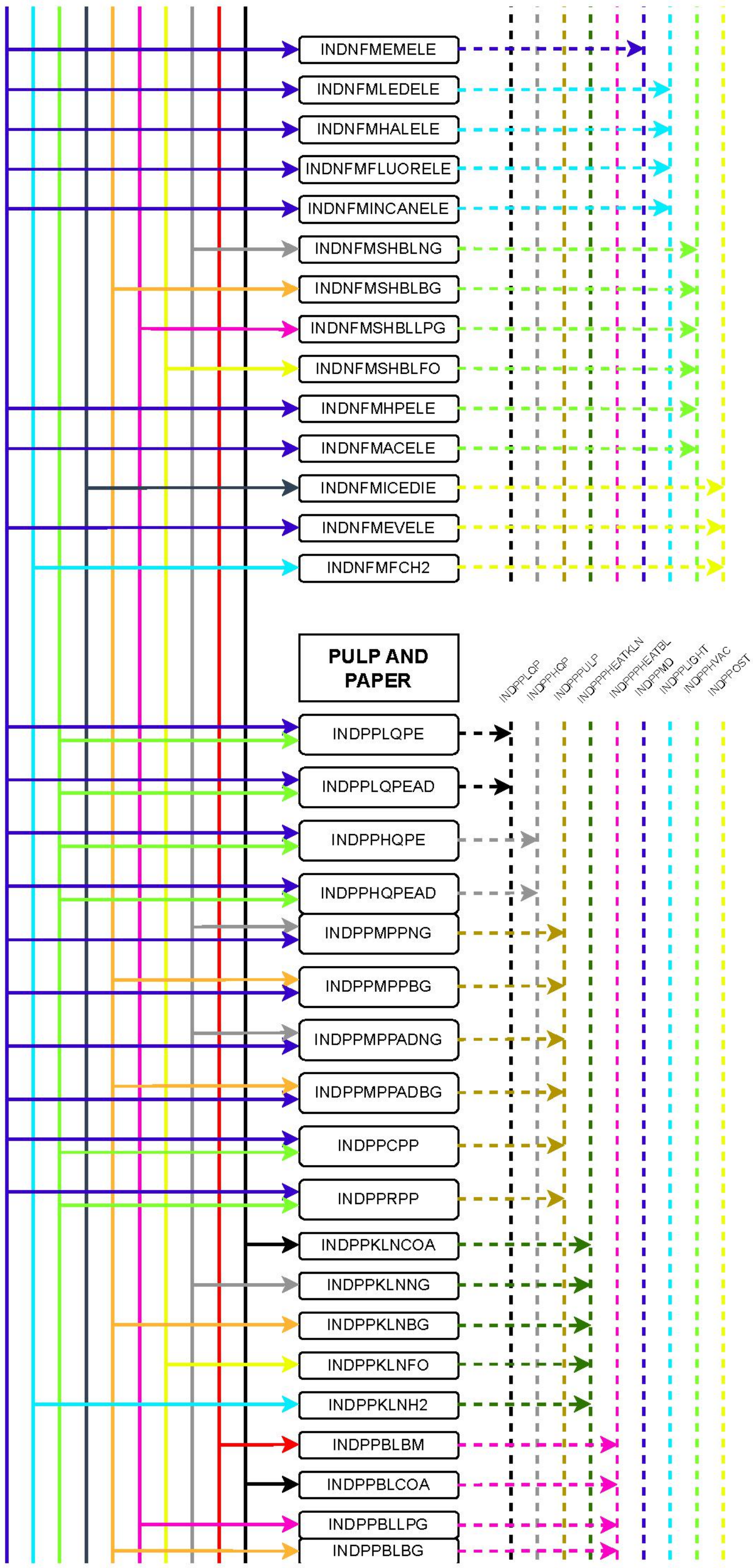

Figure A.13: Industrial sector (part 8)

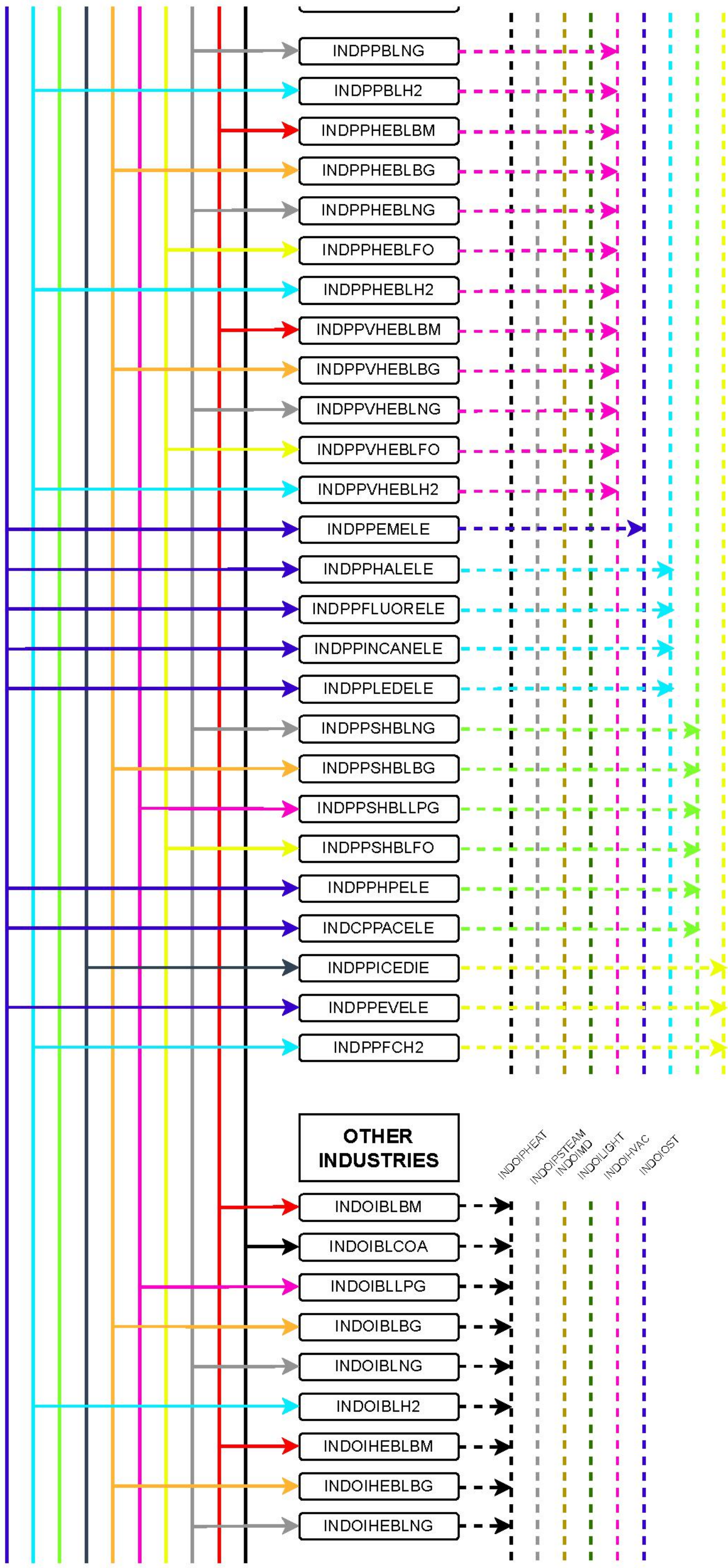

Figure A.14: Industrial sector (part 9)

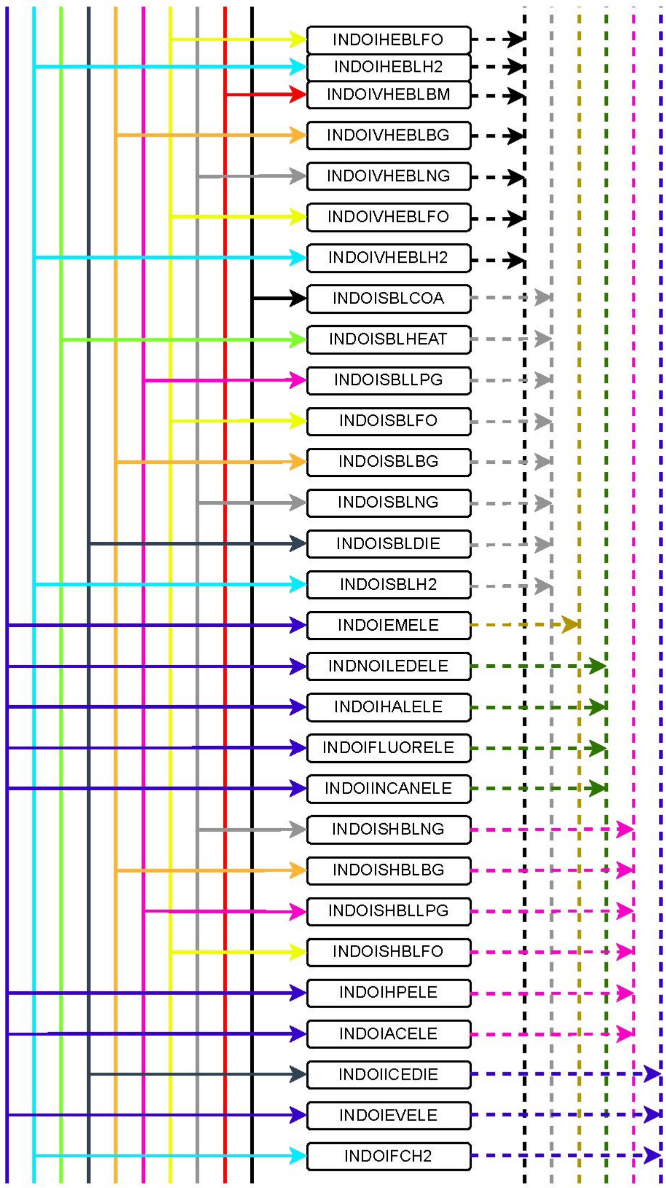

Figure A.15: Industrial sector (part 10)

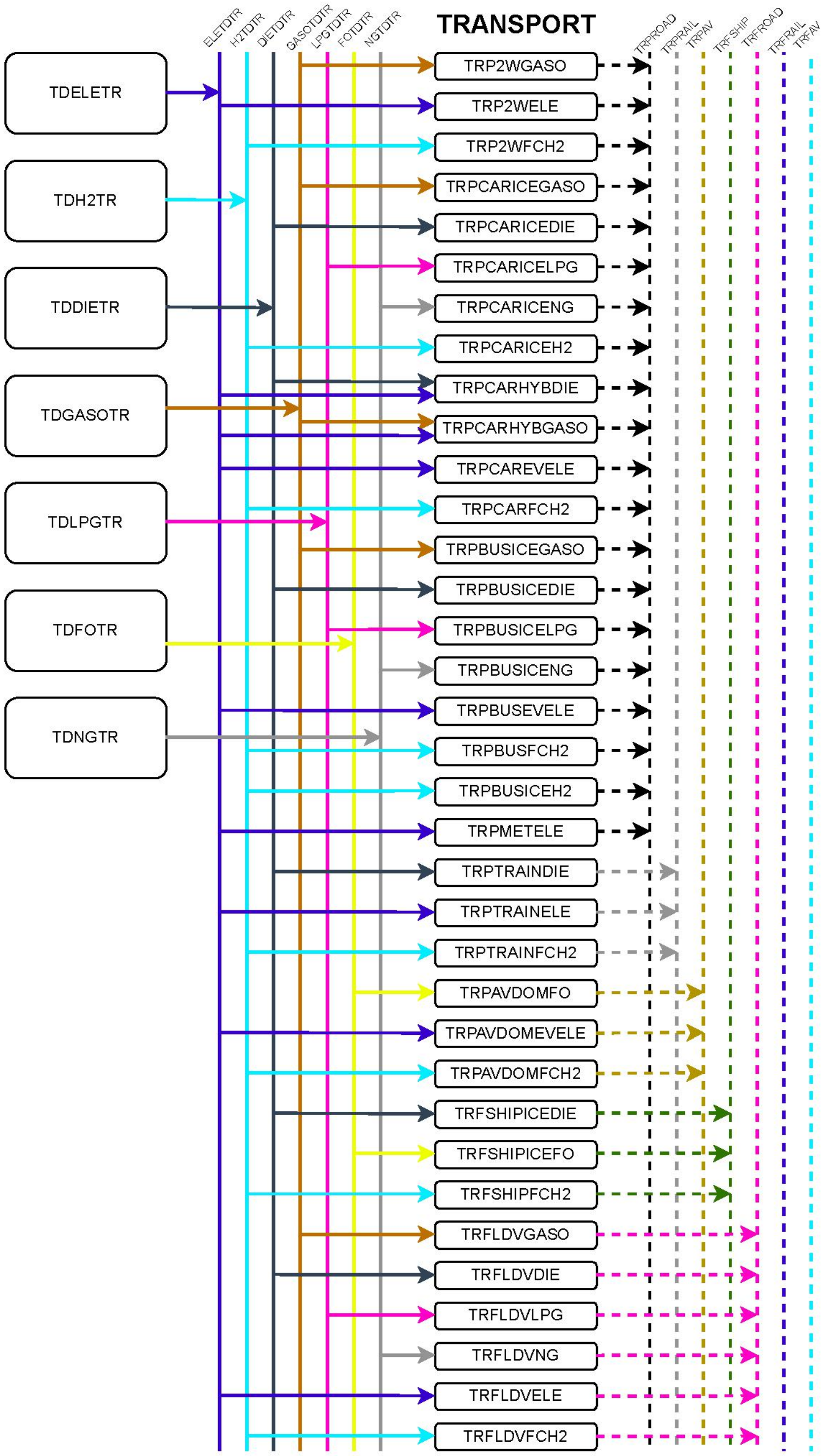

Figure A.16: Transports sector (part 1)

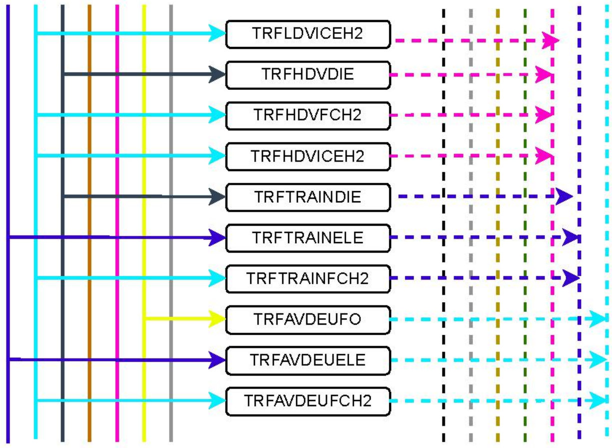

Figure A.17: Transports sector (part 2)

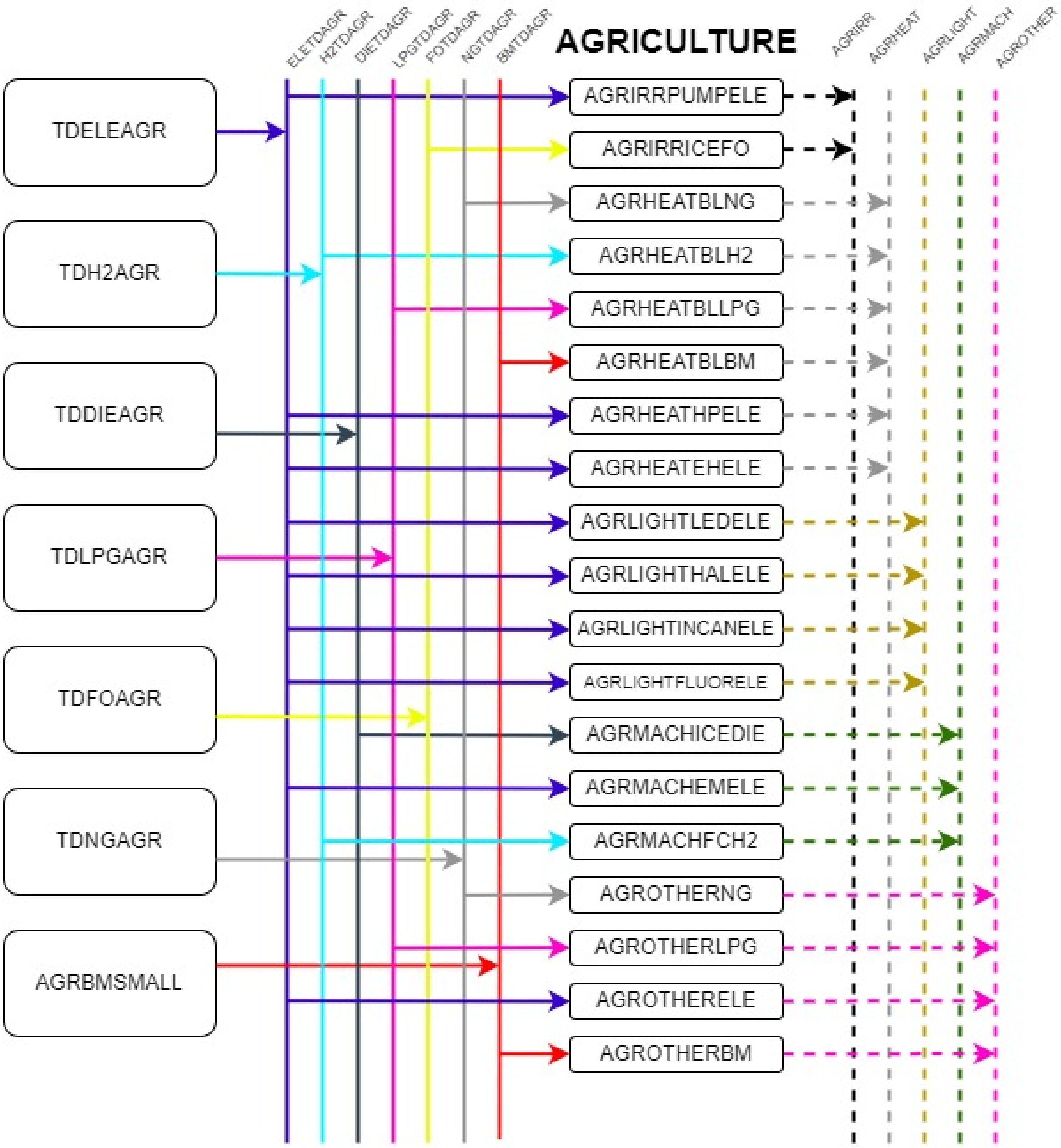

Figure A.18: Agriculture sector

Appendix B

List of the codes used for the technologies with description

This appendix contains a list of the technologies used in the model, as well as their code and description. Note that the end-use sector of each technology (if applicable) is referenced in the code: IND for industrial sector, RE for residential sector, SE for services sector, TR for transports sector and AGR for services sector.

Technology	**Code**
Coal Imports	IMPCOAL
Natural Gas Imports	IMPNG
Uranium Imports	IMPURA
Crude Oil Imports	IMPCRUDE
Diesel Imports	IMPDIE
Gasoline Imports	IMPGASO
Fuel Oil Imports	IMPFO
LPG Imports	IMPLPG
Electricity Imports	IMPELE
Biogas Imports	IMPBG
Waste Recover	RECWASTE
Biomass Collector	RECBM
Coal Power Plant	COAL_PP
Natural Gas Power Plant	NG_PP
Natural Gas Cogeneration Plant	NG_CHP
Heavy Fuel Oil Power Plant	HFO_PP
Nuclear Power Plant	NUC_PP
Large Hydro Power Plant	HYDRO_LARGE_PP
Small Hydro Power Plant	HYDRO_SMALL_PP
Large Photovoltaic Power Plant	PV_LARGE_PP
Onshore Wind Power Plant	WIND_PP

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Offshore Wind Power Plant	WIND_OFF_PP
Wave Power Plant	WAVE_PP
Biomass Power Plant	BM_PP
Biomass Cogeneration Plant	BM_CHP
Geothermal Cogeneration Plant	GEO_PP
Waste Cogeneration Plant	WASTE_CHP
Biogas Cogeneration Plant	BG_CHP
Biogas Power Plant	BG_PP
Coal Power Plant with CCUS	COAL_PP_CCUS
Natural Gas Power Plant with CCUS	NG_PP_CCUS
Biomass Power Plant with CCUS	BM_PP_CCUS
Solar Thermal Centralized Heat Production	SOLAR_THERMAL
Concentrated Solar Power Plant	CSP
Refinery	REFINERY
Hydrogen Producer via Coal gasification, large size	H2_COAL_GAS_L
Hydrogen Producer via Coal gasification, medium size	H2_COAL_GAS_M
Hydrogen Producer via Coal gasification, large size, with CCUS	H2_COAL_GAS_CCUS_L
Hydrogen Producer via Coal gasification, medium size, with CCUS	H2_COAL_GAS_CCUS_M
Hydrogen Producer via Natural gas steam reforming, large size	H2_NG_SR_L
Hydrogen Producer via Natural gas steam reforming, small size	H2_NG_SR_S
Hydrogen Producer via Natural gas steam reforming, large size, with CCUS	H2_NG_SR_CCUS_L
Hydrogen Producer via Natural gas steam reforming, small size, WITH CCUS	H2_NG_SR_CCUS_S
Hydrogen Producer via Biomass gasification, with CCUS	H2_BM_GAS_CCUS
Hydrogen Producer via Biomass gasification	H2_BM_GAS
Hydrogen Producer via Biomass Steam Reforming	H2_BM_SR
Hydrogen Producer via PEM electrolysis	H2_PEM
Hydrogen Producer via Solid Oxide Electrolyzer Cell	H2_SOEC
Hydrogen Producer via alkaline electrolysis, large size	H2_ALK_L
Hydrogen Producer via alkaline electrolysis, medium size	H2_ALK_M
Electricity Transmission	TRANSM_ELE
Hydrogen Transmission	TRANSM_H2
Heat Transmission	TRANSM_HEAT
Diesel Transmission	TRANSM_DIE
Gasoline Transmission	TRANSM_GASO
LPG transmission	TRANSM_LPG
Fuel Oil Transmission	TRANSM_FO
Natrual Gas Transmission	TRANSM_NG
Biogas Transmission	TRANSM_BG
Coal Transmission	TRANSM_COA

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Electricity distribution for the industrial sector	TDELEIND
Hydrogen distribution for the industrial sector	TDH2IND
Heat distribution for the industrial sector	TDHEATIND
Diesel distribution for the industrial sector	TDDIEIND
LPG distribution for the industrial sector	TDLPGIND
Fuel Oil distribution for the industrial sector	TDFOIND
Natural Gas distribution for the industrial sector	TDNGIND
Biogas distribution for the industrial sector	TDBGIND
Coal distribution for the industrial sector	TDCOAIND
Electricity distribution for the residential sector	TDELERE
Hydrogen distribution for the residential sector	TDH2RE
Heat distribution for the residential sector	TDHEATRE
Fuel Oil distribution for the residential sector	TDFORE
LPG distribution for the residential sector	TDLPGRE
Natural Gas distribution for the residential sector	TDNGRE
Electricity distribution for the services sector	TDELESE
Hydrogen distribution for the services sector	TDH2SE
Heat dstribution for the services sector	TDHEATSE
Fuel Oil distribution for the services sector	TDFOSE
LPG distribution for the services sector	TDLPGSE
Natural Gas distribution for the services sector	TDNGSE
Electricity distribution for the transports sector	TDELETR
Hydrogen distribution for the transports sector	TDH2TR
Diesel distribution for the transports sector	TDDIETR
Gasoline distribution for the transports sector	TDGASOTR
LPG distribution for the transports sector	TDLPGTR
Fuel Oil distribution for the transports sector	TDFOTR
Natural Gas distribution for the transports sector	TDNGTR
Electricity distribution for the agriculture sector	TDELEAGR
Hydrogen distribution for the agriculture sector	TDH2AGR
Diesel distribution for the agriculture sector	TDDIEAGR
LPG distribution for the agriculture sector	TDLPGAGR
Fuel Oil distribution for the agriculture sector	TDFOAGR
Natural Gas distribution for the agriculture sector	TDNGAGR
Air conditioner for HVAC use	INDAC
Advanced Membrane Producer	INDCHAMP
Advanced Membrane Producer Improvement	INDCHAMPI
Biomass boiler	INDBLBM
Coal boiler	INDBLCOA
LPG boiler for HVAC use	INDBLLPGSH

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Biogas boiler for HVAC use	INDBLBGSH
Natural gas boiler for HVAC use	INDBLNGSH
Fuel oil boiler for HVAC use	INDBLOilPSH
LPG boiler	INDBLLPG
Biogas boiler	INDBLBG
Natural Gas boiler	INDBLNG
Hydrogen boiler	INDBLH2
Fuel oil boil	INDBLOILP
Diesel ICE for onsite transportation use	INDICEDIE
Electric Vehicle for onsite transportation use	INDEVELE
Hydrogen fuel cell vehicle for onsite transportation use	INDFCH2
Electric compressor for refrigeration use	INDCMPELE
Fluorescent lightbulb	INDFLRTELE
High efficiency biomass boiler	INDHEBLBM
High efficiency biogas boiler	INDHEBLBG
High efficiency natural gas boiler	INDHEBLNG
High efficiency fuel oil boiler	INDHEBLOilP
High efficiency hydrogen boiler	INDHEBLH2
Halogen lightbulb	INDHLGELE
Heat pump for HVAC use	INDHPELE
Incandescent lightbulb	INDINCTELE
LED lightbulb	INDLEDELE
Electric motor for machine drive use	INDMTRELE
Plasma Arc Decomposition fed by natural gas	INDCHPAC
Plasma Arc Decomposition fed by biogas	INDCHPACBG
Coal steam boiler	INDSBLCOA
Heat steam boiler	INDSBLHEAT
LPG steam boiler	INDSBLLPG
Fuel oil steam boiler	INDSBLOil
Biogas steam boiler	INDSBLBG
Natural gas steam boiler	INDSBLNG
Hydrogen steam boiler	INDSBLH2
Very high efficiency biomass boiler	INDVHEBLBM
Very high efficiency biogas boiler	INDVHEBLBG
Very high efficiency natural gas boiler	INDVHEBLNG
Very high efficiency fuel oil boiler	INDVHEBLOilP
Very high efficiency hydrogen boiler	INDVHEBLH2
Dry process equipment (cement)	INDCMLM_DPE
Finished Cement Producer equipment	INDCMLM_FCPE
Coal Kiln	INDCMLMKLNCOA

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Natural gas kiln	INDCMLMKLNNG
Biogas kiln	INDCMLMKLNBG
Fuel Oil kiln	INDCMLMKLNOilP
Biomass kiln	INDKLNBM
Electrical kiln	INDKLNELE
Biogas kiln	INDKLNBG
Natural gas kiln	INDKLNNG
Quick lime Producer equipment	INDCMLMQLP
Flat Glass Producer equipment fed by natural gas	INDCRGLFPE
Flat Glass Producer equipment fed by biogas	INDCRGLFPEBG
Flat glass Producer equipment with heat recovery fed by natural gas	INDCRGLFPEHR
Flat glass prodcution equipment with heat recovery fed by biogas	INDCRGLFPEHRBG
Hollow glass Producer equipment fed by natural gas	INDCRGLGHE
Hollow glass Producer equipment fed by biogas	INDCRGLGHEBG
Hollow glass Producer equipment with heat recovery fed by natural gas	INDCRGLGHEHR
Hollow glass Producer equipment with heat recovery fed by biogas	INDCRGLGHEHRBG
Recycling glass Producer equipment fed by natural gas	INDCRGLGLRE
Recycling glass Producer equipment fed by biogas	INDCRGLGLREBG
Recycling glass Producer equipment with improved melting fed by natural gas	INDCRGLGLREIM
Recycling glass Producer equipment with improved melting fed by biogas	INDCRGLGLREIMBG
Biomass oven	INDOVNBM
Coal oven	INDOVNCOA
Diesel oven	INDOVNDIE
Electric oven	INDOVNELE
Biogas oven	INDOVNBG
Natural gas oven	INDOVNNG
Fuel oil oven	INDOVNOilP
Electric Arc Furnace fed by Natural Gas	INDISEAF
Electric Arc Furnace fed by biogas	INDISEAFBG
Iron and steel Producer technologies fed by natural gas	INDISISPT
Iron and steel Producer technologies fed by biogas	INDISISPTBG
Finished aluminium Producer equipment fed by natural gas	INDNFMFAP
Finished aluminium Producer equipment fed by biogas	INDNFMFAPBG
Inert Anodes to produce crude aluminium fed by natural gas	INDNFMIA
Inert Anodes to produce crude aluminium fed by biogas	INDNFMIABG
Chemical pulp Producer	INDPPCPP
High quality paper equipment	INDPPHQPE
High quality paper equipment with advanced drives	INDPPHQPEAD
Low quality paper equipment	INDPPLQPE
Low quality paper equipment with advanced drives	INDPPLQPEAD

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Mechanical pulp Producer fed by natural gas	INDPPMPP
Mechanical pulp Producer fed by biogas	INDPPMPPBG
Mechanical pulp Producer airless drying fed by natural gas	INDPPMPPAD
Mechanical pulp prodution airless drying fed by biogas	INDPPMPPADBG
Recycling pulp prdocution	INDPPRPP
Electric Arc Furnace fed by hydrogen	INDISEAFH2
Hydrogen oven	INDOVNH2
Hydrogen kiln	INDKLNH2
Hydrogen kiln	INDCMLMKLNH2
Biomass for other thermal uses	INDOTHERBM
Natural gas for other thermal uses	INDOTHERNG
LPG for other thermal uses	INDOTHERLPG
Fuel oil for other thermal uses	INDOTHEROilP
Electricity for other electrical uses	INDOTHERELE
Biogas for other thermal uses	INDOTHERBG
Diesel steam boiler	INDSBLDIE
Fuel Oil kiln	INDKLNOilP
Coal for other thermal uses	INDOTHERCOA
Heat for other thermal uses	INDOTHERHEAT
Air Conditioner	RESCOOLACELE
Centralized Air Conditioner	RESCOOLCACELE
High efficiency clothes washer and dryer	RECLOWHEELE
Low efficiency clothes washer and dryer	RECLOWLEELE
Electrical stove	RECOOKELE
LPG stove	RECOOKLPG
Natural gas stove	RECOOKNG
Hydrogen stove	RECOOKH2
Biomass heater	REDHWHEATERBM
LPG heater	REDHWHEATERLPG
Natural gas heater	REDHWHEATERNG
Fuel oil heater	REDHWHEATERFO
Hydrogen heater	REDHWHEATERH2
Soler thermal	REDHWSOLTHERM
Thermoaccumulator	REDHWTERMOELE
Biomass boiler	REDHWSHEATBLBM
LPG boiler	REDHWSHEATBLLPG
Natural gas boiler	REDHWSHEATBLNG
Fuel oil boiler	REDHWSHEATBLFO
Hydrogen boiler	REDHWSHEATBLH2
High efficiency dishwasher	REDISHWHEELE

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Low efficiency dishwasher	REDISHWLEELE
Small appliances equipment	RESAPPELE
Biomass closed fireplace	RESHCFPBM
Biomass open fireplace	RESHOFPBM
Heat pump	RESHEATCOOLHPELE
Small heating equipment	RESHAPPLELE
Fluorescent lightbulb	RELIGHTFLUORELE
Halogen lightbulb	RELIGHTHALELE
Incandescent lightbulb	RELIGHTINCANELE
LED lightbulb	RELIGHTLEDELE
High efficiency refrigerator	REREFHEELE
Low efficiency refrigerator	REREFLEELE
Heat exchanger	REHXHEAT
Air Conditioner	SESCOOLACELE
Centralized Air Conditioner	SESCOOLCACELE
Biomass heater	SEDHWHEATERBM
Natural gas heater	SEDHWHEATERNG
Hydrogen heater	SEDHWHEATERH2
LPG heater	SEDHWHEATERLPG
Fuel oil heater	SEDHWHEATERFO
Soler thermal	SEDHWSOLTHERM
Thermoaccumulator	SEDHWTHERMOELE
Biomass boiler	SEDHWSHEATBLBM
LPG boiler	SEDHWSHEATBLLPG
Natural gas boiler	SEDHWSHEATBLNG
Fuel oil boiler	SEDHWSHEATBLFO
Hydrogen boiler	SEDHWSHEATBLH2
High efficiency freezing compressor	SEFREEZHEELE
Low efficiency freezing compressor	SEFREEZLEELE
Biomass closed fireplace	SESHEATCFPBM
Biomass open fireplace	SESHEATHPELE
Fluorescent lightbulb	SELIGHTFLUORELE
Halogen lightbulb	SELIGHTHALELE
Incandescent lightbulb	SELIGHTINCANELE
LED lightbulb	SELIGHTLEDELE
High efficiency refrigerator	SEREFHEELE
Low efficiency refrigerator	SEREFLEELE
Small appliances equipment	SESAPPELE
Electrical stove	SECOOKELE
Natural gas stove	SECOOKNG

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Hydrogen stove	SECOOKH2
LPG stove	SECOOKLPG
High efficiency dishwasher	SEDISHWHEELE
Low efficiency dishwasher	SEDISHWLEELE
High efficiency clothes washer and dryer	SECLOWHEELE
Low efficiency clothes washer and dryer	SECLOWLEELE
Heat Exchanger	SEHXHEAT
Gasoline 2 wheeler for passenger transport	TRP2WGASO
Electrical 2 wheeler for passenger transport	TRP2WELE
Hydrogen fuel cell 2 wheeler for passenger transport	TRP2WFCH2
Gasoline ICE car for passenger transport	TRPCARICEGASO
Diesel ICE car for passenger transport	TRPCARICEDIE
LPG ICE car for passenger transport	TRPCARICELPG
Natural gas ICE car for passenger transport	TRPCARICENG
Hydrogen ICE car for passenger transport	TRPCARICEH2
Diesel hybrid car for passenger transport	TRPCARHYBDIE
Gasoline hybrid car for passenger transport	TRPCARHYBGASO
Electrical car for passenger transport	TRPCAREVELE
Hydrogen fuel cell car for passenger transport	TRPCARFCH2
Gasoline ICE bus for passenger transport	TRPBUSICEGASO
Diesel ICE bus for passenger transport	TRPBUSICEDIE
LPG ICE bus for passenger transport	TRPBUSICELPG
Natural gas ICE bus for passenger transport	TRPBUSICENG
Electrical bus for passenger transport	TRPBUSEVELE
Hydrogen fuel cell bus for passenger transport	TRPBUSFCH2
Hydrogen ICE bus for passenger transport	TRPBUSICEH2
Electrical metro tram for passenger transport	TRPMETELE
Diesel ICE train for passenger transport	TRPTRAINDIE
Electrical train for passenger transport	TRPTRAINELE
Hydrogen fuel cell train for passenger transport	TRPTRAINFCH2
Fuel oil ICE airplane for domestic passanger transport	TRPAVDOMFO
Electrical airplane fordomestic passanger transport	TRPAVDOMEVELE
Hydrogen fuel cell airplane for domestic passanger transport	TRPAVDOMFCH2
Diesel ICE ship for freight transport	TRFSHIPICEDIE
Fuel oil ICE ship for freight transport	TRFSHIPICEFO
Hydrogen fuel cell ship for freight transport	TRFSHIPFCH2
Gasoline ICE light duty vehicle for freight transport	TRFLDVGASO
Diesel ICE light duty vehicle for freight transport	TRFLDVDIE
LPG ICE light duty vehicle for freight transport	TRFLDVLPG
Natural gas ICE light duty vehicle for freight transport	TRFLDVNG

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Electrical light duty vehicle for freight transport	TRFLDVELE
Hydrogen fuel cell light duty vehicle for freight transport	TRFLDVFCH2
Hydrogen ICE light duty vehicle for freight transport	TRFLDVICEH2
Diesel heavy duty vehicle for freight transport	TRFHDVDIE
Hydrogen fuel cell heavy duty vehicle for freight transport	TRFHDVFCH2
Hydrogen ICE heavy duty vehicle for freight transport	TRFHDVICEH2
Diesel ICE train for freight transport	TRFTRAINDIE
Electrical train for freight transport	TRFTRAINELE
Hydrogen fuel cell train for freight transport	TRFTRAINFCH2
Fuel oil ICE airplane for domestic + intra-EU freight transport	TRFAVDEUFO
Electrical airplane for domestic + intra-EU freight transport	TRFAVDEUELE
Hydrogen fuel cell airplane for domestic + intra-EU freight transport	TRFAVDEUFCH2
Electrical pump for irrigation use	AGRIRRPUMPELE
Fuel oil ICE for irrigation use	AGRIRRICEFO
Natural gas boiler for heat use	AGRHEATBLNG
Hydrogen boiler for heat use	AGRHEATBLH2
Fuel oil boiler	AGRHEATBLFO
Diesel boiler	AGRHEATBLDIE
LPG boiler for heat use	AGRHEATBLLPG
Biomass boiler for heat use	AGRHEATBLBM
Electrical heat pump	AGRHEATHPELE
LED lightbulb	AGRLIGHTLEDELE
Halogen lightbulb	AGRLIGHTHALELE
Incandescent lightbulb	AGRLIGHTINCANELE
Fluorescent lightbulb	AGRLIGHTFLUORELE
Diesel ICE for machinery use	AGRMACHICEDIE
Electrical motor for machinery use	AGRMACHEMELE
Hydrogen fuel cell for machinery use	AGRMACHFCH2
Other natural gas uses	AGRVENTFANELE
Other LPG uses	AGRSAPPELE
Decentralized photovoltaic electricity producer	INDPVSMALL
Decentralized wind electricity producer	INDWINDSMALL
Decentralized biomass collector	INDBMSMALL
Decentralized photovoltaic electricity producer	REPVSMALL
Decentralized wind electricity producer	REWINDSMALL
Decentralized biomass collector	REBMSMALL
Decentralized photovoltaic electricity producer	SEPVSMALL
Decentralized wind electricity producer	SEWINDSMALL
Decentralized biomass collector	SEBMSMALL
Decentralized biomass collector	AGRBMSMALL

Appendix C

List of the codes used for fuels with description

This appendix contains a list of the fuels used in the model, as well as their code and description. Note that the end-use sector of each fuel (if applicable) is referenced in the code: IND for industrial sector, RE for residential sector, SE for services sector, TR for transports sector and AGR for services sector. Fuels with just TD belong to the first level of transmission and distribtuion and the ones with XXXTDYY belong in the second (XXX refers to the carrier code and YY to the sector code).

Fuel	**Code**
Coal after imports	COA
Natural gas after imports	NG
Uranium after imports	URA
Crude oil after imports	CRUDE
Biogas after imports	BG
Waste after being recovered	WASTE
Biomass after being collected	BM
Electricity after imports and centralized production	ELE
Heat after centralized production	HEAT
Diesel after imports and crude oil transformation	DIE
Gasoline after imports and crude oil transformation	GASO
LPG after imports and crude oil transformation	LPG
Fuel oil after crude oil transformation	FO
Hydrogen after imports and centralized production	H2
Electricity after transmission	ELETD
Hydrogen after transmission	H2TD
Heat after transmission	HEATTD
Diesel after transmission	DIETD
Gasoline after transmission	GASOTD

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LPG after transmission	LPGTD
Fuel oil after transmission	FOTD
Natural Gas after transmission	NGTD
Biogas after transmission	BGTD
Coal after transmission	COATD
Electricity after transmission and distribution	ELETDIND
Hydrogen after transmission and distribution	H2TDIND
Heat after transmission and distribution	HEATTDIND
Diesel after transmission and distribution	DIETDIND
Biogas after transmission and distribution	BGTDIND
LPG after transmission and distribution	LPGTDIND
Fuel Oil after transmission and distribution	FOTDIND
Natural gas after transmission and distribution	NGTDIND
Biomass after decentralized collection	BMTDIND
Coal after transmission and distribution	COATDIND
Ammonia production	INDCHAM
Aluminium prodution	INDNFMAL
Crude aluminium prodution	INDNFMCAL
Chlorine production	INDCHCL
Clinker production	INDCMLMCLK
Cement production	INDCMLMCMT
Crude steel production	INDISCSTEEL
Flat glass prodution	INDCRGLGF
Hollow glass production	INDCRGLGH
Boiler Process Heat	INDPHEATBL
Oven Process Heat	INDPHEATOV
Kiln process heat	INDPHEATKILN
Kiln process heat	INDPHEATCMKILN
HVAC	INDHVAC
High quality paper production	INDPPHQP
Lighting	INDLIGHT
Lime production	INDCMLMLM
Low quality paper production	INDPPLQP
Machine Drive	INDMD
On Site Transportation	INDOST
Pulp production	INDPPPULP
Refrigeration	INDRFR
Process Steam	INDSTEAM
Steel production	INDISSTEEL
Other thermal uses	INDOTHERTHERM

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Other electrical uses	INDOTHERUELE
Electricity after transmission and distribution	ELETDRE
Hydrogen after transmission and distribution	H2TDRE
Biomassafter decentralized collection	BMTDRE
Fuel oil after transmission and distribution	FOTDRE
LPG after transmission and distribution	LPGTDRE
Natural gas after transmission and distribution	NGTDRE
Cooling	RECOOL
Clothes washing	RECLOW
Cooking	RECOOK
Domestic Hot Water production	REDHW
Dishwashing	REDISH
Small Appliances	RESMALLAPPL
Space Heating	RESHEAT
Lighting	RELIGHT
Refrigeration	REREF
Electricity after transmission and distribution	ELETDSE
Hydrogen after transmission and distribution	H2TDSE
Biomass after decentralized collection	BMTDSE
Fuel Oil after transmission and distribution	FOTDSE
LPG after transmission and distribution	LPGTDSE
Natural gas after transmission and distribution	NGTDSE
Space heating	SESHEAT
Domestic Hot Water production	SEDHW
Cooling	SECOOL
Cooking	SECOOK
Lighting	SELIGHT
Refrigeration	SEREF
Dishwashing	SEDISH
Freezing	SEFREEZ
Clothes washing	SECLOW
Small Appliances	SESMALLAPPL
Electricity after transmission and distribution	ELETDTR
Hydrogen after transmission and distribution	H2TDTR
Diesel after transmission and distribution	DIETDTR
Gasoline after transmission and distribution	GASOTDTR
LPG after transmission and distribution	LPGTDTR
Fuel oil after transmission and distribution	FOTDTR
Natural gas after transmission and distribution	NGTDTR
Road passenger transportation by 2 wheel vehicles	TRPROAD2W

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Road passenger transportation by car	TRPROADCAR
Road passenger transportation by bus	TRPROADBUS
Rail passenger transportation	TRPRAIL
Metro passenger transportation	TRPMETRO
Passenger aviation	TRPAV
Freight shipping	TRFSHIP
Road freight transportation by light duty vehicles	TRFROADLDV
Road freight transportation by heavy duty vehicles	TRFROADHDV
Rail freight transportation	TRFRAIL
Freight aviation	TRFAV
Electricity after transmission and distribution	ELETDAGR
Hydrogen after transmission and distribution	H2TDAGR
Diesel after transmission and distribution	DIETDAGR
LPG after transmission and distribution	LPGTDAGR
Fuel oil after transmission and distribution	FOTDAGR
Natural gas after transmission and distribution	NGTDAGR
Biomass after decentralized collection	BMTDAGR
Irrigation	AGRIRR
Heating	AGRHEAT
Lighting	AGRLIGHT
Machinery	AGRMACH
Ventilation	AGRVENT
Small Appliances	AGRSMALLAPPL

Appendix D

Repository with the input data of the model

This appendix contains a link to a repository where the input techno-economic parameters and functional parameters of the model are listed. This parameters are destined to be used with OSeMOSYS.

https://github.com/afonso-ss/Techno-economic-parameters-for-the-Portuguese-energy-system-model-developed-in-OSeMOSYS.git