Politecnico di Torino

Master's Degree Thesis

Macroeconomic Implications of the Energy Transition: Combine bottom-up modelling of the energy transition with implications in terms of economic growth and employment

Master's degree course in Environmental and Land Engineering: Climate Change

Thesis Advisor:
Alessandro Casasso
Tiago Domingos

Candidate:
Lorenzo Maffia
s330810

July 2025

Abstract

This thesis develops a comprehensive macroeconomic-energy model to determine two scenarios from Portugal by 2050: a Business-as-Usual and an Optimistic one aligned with the national climate roadmap RNC2050. It unifies socioeconomic drivers, such as human labour and capital, with energy system processes, using an exergy-based methodology that allows calculation of Total Factor Productivity and carbon emissions as endogenous outcomes. Through the integration of sectoral investments, renewable energy cost projections and end-use final exergy distribution by sectors, carriers and end-uses, the model estimates CO_2 emissions and carbon intensity for both scenarios. Outcomes show that although both scenarios predict decreasing emissions, only the Optimistic Scenario approaches carbon-neutrality, driven by widespread electrification, large-scale adoption of renewables and structural transformation of the economy. The comparison between the roadmap and the Optimistic Scenario shows how similar they are in terms of CO_2 emissions and how they differ, for example, in terms of methodology, particularly with regard to exergy measures, TFP and endogenous GDP. The thesis, indeed, reflects on missing elements in both the RNC2050 and the model itself and overall, the findings highlight the importance of ambitious, comprehensive action to achieve a sustainable and economically sound transition.

Keywords

Energy Transition

Exergy Analysis

Macroeconomics

Carbon Neutrality

RNC2050

CO_2 Emissions

Aggregate Efficiency

Contents

Abstract 4

Keywords 5

List of Figures 10

List of Tables 12

Acronyms 14

1. Introduction 16

1.1 Background: Climate change and the need for action 16

1.2 Linking energy, economy and climate policies 16

1.3 Portuguese roadmap to carbon neutrality – RNC2050 17

1.4 Objectives 17

1.5 Thesis outline 18

1.6 Contribution of this thesis 18

2. State of the Art 19

2.1 The Role of Scenario Modelling in Climate and Energy Planning 19

2.2 Portuguese Climate Roadmaps: RNC2050 and MEET2030 19

2.3 The Energy-Economy Nexus: From Energy Inputs to Economic Output 21

2.4 Exergy, Efficiency, and Macroeconomic Integration 22

3. Model Structure and Data Assumptions 23

3.1 Human Labour: Structure and Assumptions 23

3.2 Capital Accumulation and Investment in Renewables 24

3.3 Renewable Energy Costs and Installed Power Capacity 25

3.4 Total Factor Productivity and GDP Computation 27

3.5 Energy-Exergy Allocation and Efficiency Estimation 27

3.6 CO_2 Emissions and Carbon Intensity 28

3.7 Model scheme 28

3.8 Mathematical Formulation of the Model 30

3.8.1 Human Labour 30

3.8.2 Capital Stock 30

3.8.3 Adjustment for Renewable Investments (Optimistic Scenario) 30

3.8.4 GDP and Total Factor Productivity 31

3.8.5 Total Useful and Final Exergy 31

3.8.6 Exergy Allocation and Aggregate Efficiency 31

3.8.7 CO_2 Emissions Calculation 32

3.8.8 Carbon Intensity 33

4. Results 34

4.1 Human Labour 34

4.2 Capital Stock 34

4.3 Total Factor Productivity and GDP 35

4.4 Renewable Capacity 36

4.5 Total Final Exergy and Shares of Final Exergy 37

4.6 Total Final Exergy - Electricity 40

4.7 Total CO_2 Emissions 41

4.8 Carbon Intensity 42

5. Discussion 44

5.1 Interpretation of the social variables 44

5.2 Investment, Capital and GDP 45

5.3 Assumptions on Costs and Efficiencies 45

5.4 Future Renewable Deployment 46

5.5 Comparison of Total Final Exergy 46

5.6 Emissions Trajectories and Carbon Neutrality **47**

6. Conclusion **48**

6.1 Overview of Key Results **48**

6.2. On the Adequacy of the 2050 Carbon Neutrality Target **48**

6.3. Gaps and Limitations in the Model **49**

6.4. Missing Components in RNC2050 and Comparative Value of This Thesis **50**

6.5. Contribution to European Modelling Frameworks: Relevance to the MAPS Project **50**

6.6. Recommendations for Future Work **51**

Bibliography **53**

Appendices **54**

List of Figures

Figure 3.1 - Evolution of the renewable technology costs 26

Figure 3.2 – Conceptual map of the model based on (Fidalgo Pinto Veloso da Silva et al., 2020) .. 29

Figure 4.1 – Historical data and future projection of HL for both the scenarios 34

Figure 4.2 – Evolution of Total Capital Stock for both the scenarios 35

Figure 4.3 – Historical data and future projection of TFP for both the scenarios 35

Figure 4.4 - Evolution of GDP for both the scenarios and for the RNC2050 36

Figure 4.5 - Evolution of the total renewable power installed for both the scenarios 36

Figure 4.6 – Shares of Final Exergy across sectors and Total Final Exergy, BaU Scenario 37

Figure 4.7 - Shares of Final Exergy across sectors and Tota Final Exergy, Optimistic Scenario 38

Figure 4.8 – Shares of Final Exergy in the transport sector across carriers, BaU scenario 38

Figure 4.9 - Shares of Final Exergy in the industry sector across carriers, BaU scenario 39

Figure 4.10 - Shares of Final Exergy in the transport sector across carriers, Optimistic scenario . 40

Figure 4.11 - Shares of Final Exergy in the industry sector across carriers, Optimistic scenario... 40

Figure 4.12 – Total Electricity Demand and Renewable Electricity, BaU scenario 41

Figure 4.13 - Total Electricity Demand and Renewable Electricity, Optimistic scenario 41

Figure 4.14 – Total CO_2 Emissions for both the scenarios...42

Figure 4.16 – Carbon Intensity for both the scenarios..43

Figure 5.1 – Evolution of the Total Final Exergy for the three cases 47

List of Tables

Table 3.1 – Renewable energies costs per GW 26

Table A.1 – Social variables, BaU scenario 55

Table A.2 – Social variables, Optimistic Scenario 56

Table B.3 – Historical Capital 57

Table B.4 – Historical Investments 58

Table B.5 – Historical Depreciations 58

Table B.6 – Historical means from 2012 to 2022 59

Table B.7 – RNC2050 Investments De-actualized, constant price 2015 59

Table C.8 – GW of Renewable Power Installed, BaU Scenario 60

Table C.9 – GW of Renewable Power Installed, Optimistic Scenario 62

Table D.10 – Shares of Final Exergy across sectors, BaU Scenario 62

Table D.11 – Shares of Final Exergy across sectors, Optimistic Scenario 63

Table D.12 – Shares of Final Exergy, sectors across carriers, BaU Scenario 64

Table D.13 – Shares of Final Exergy, sectors across carriers, Optimistic Scenario 66

Table E.14 – Efficiencies 67

Table E.15 – Aggregate Efficiencies 68

Acronyms

IST	Instituto Superior Técnico
RNC	Roteiro para a Neutralidade Carbonica
GDP	Gross Domestic Product
TFP	Total Factor Productivity
BAU	Business as usual
INE	Instituto Nacional de Estatística
APA	Agência Portuguesa do Ambiente
ILO	International Labour Organization
EPRI	Electric Power Research Institute
IRENA	International Renewable Energy Agency
CCS	Carbon Capture and Storage
CCUS	Carbon Capture Utilization and Storage

1. Introduction

1.1 Background: Climate change and the need for action

Human development has always tended to pursue economic growth and societal well-being. However, this has come at a significant environmental cost. The impacts of climate change, like rising temperatures, extreme events, loss of biodiversity and environmental degradation, are evident worldwide and most of the countries are cooperating, trying to reduce the damage already present and eventually to invert the trends. A milestone in the global effort to combat climate change is the Paris Agreement, adopted in 2015 by 196 countries. This international accord sets three key objectives, namely, to limit the global temperature increase to well below 2 °C and continue efforts to limit it to 1.5 °C compared to pre-industrial levels; to strengthen the capacity to adapt to the adverse effects of climate change and promote resilience; to align financial flows with a pathway towards low-carbon, climate-resilient development. Despite the urgency of these goals, the trajectory remains worrying, since 2024 was the hottest year on record, with a global average temperature increase of 1.6 °C. This event underlines the need for immediate and transformative action.

1.2 Linking energy, economy and climate policies

Achieving the goals set by the Paris Agreement will require a profound decarbonisation of all sectors of society. For this reason, in order to fully understand the opportunities and constraints of this transition, it is essential to clarify the link between energy systems and economic development. Energy is a fundamental factor for all productive activities, as they all depend on its availability and conversion into usable forms. However, to accurately assess this link, it is best to go beyond traditional aggregate energy consumption metrics and examine the energy conversion chain, which can be divided into three main stages:

- Primary energy, which refers to naturally occurring energy sources, such as crude oil, coal, natural gas, solar radiation, and wind.
- Final energy, which is the type of energy available to end users after extraction, processing, conversion and transmission, such as electricity, gasoline and diesel.
- Useful energy, which is the energy that has been changed into a form that can be used directly to provide services like heating, cooling, lighting, and mechanical work.

At each step of the chain, losses occur due to inefficiencies of conversion and distribution technologies. However, they are not only dictated by technical constraints, but also by the laws of thermodynamics and for this reason, the concept of exergy becomes central.

Exergy measures the maximum amount of work that can be obtained from a system when it reaches equilibrium with a reference environment and, while energy is conserved, as stated by the first law of thermodynamics, exergy is partially lost at each stage of conversion due to irreversibility, according to the second law of thermodynamics. In this context, useful exergy, which is the last step in the chain, is the most accurate way to understand the physical basis of economic production. It shows how much energy is really needed for production and consumption, so it is the closest thing to the real economic value of energy. Several real-world studies have shown that there is a strong and stable link between useful exergy and economic growth. Changes in how useful exergy is distributed and used in different sectors of the UK are very closely linked to changes in GDP and structural changes in the economy, as shown by Serrenho et al. (2014). For Portugal, Santos et al. (2021) also demonstrated that there is a statistically significant long-term linear relationship between residual total factor productivity and the aggregate efficiency of final exergy relative to useful exergy, defined as the ratio of useful exergy to final exergy consumed. This showed that TFP, often treated as a residual, can be physically explained by improvements in the capacity of the energy system.

For these reasons, the adoption of useful exergy as a primary energy parameter to link energy to economic modelling is crucial and helpful. The connection between aggregate exergy efficiency and TFP allows for an understanding of how improvements in energy quality, structure, and end-use efficiency, such as increased electrification, can generate economic growth, enabling a more realistic analysis of how energy transitions interact with economic development and climate policies.

1.3 Portuguese roadmap to carbon neutrality – RNC2050

Recognising the urgency of climate action, Portugal, as many other countries, published in 2019 the Roteiro para a Neutralidade Carbónica 2050 (RNC2050). This roadmap sets out a strategy to achieve carbon neutrality by 2050, balancing economic development with environmental sustainability. The RNC2050 outlines decarbonisation pathways for different sectors, such as energy, transport, industry, agriculture and construction, and quantifies the investments and transformations needed. Importantly, it recognises the need for an integrated policy that aligns economic planning, energy system transformation and climate goals.

However, while the RNC2050 provides valuable insight and data sets, it does not fully integrate the macroeconomic implications of the energy transition, particularly in terms of energy quality and efficiency and its connection to economic indicators, such as GDP, Capital and Labour.

1.4 Objectives

This thesis, based on (Fidalgo Pinto Veloso da Silva et al., 2020), aims to develop a model that explores the long-term interaction between economic variables and energy systems and uses exergy as a central concept, overcoming the limitations of the RNC2050. The model takes into account inputs, such as capital, labour, investment in renewables and shares of final exergy across sectors, carriers and end-uses and finally estimates the resulting CO_2 emissions.

Two main scenarios are analysed:

1. Business-as-Usual (BAU) scenario, which assumes the absence of major structural changes.
2. Optimistic scenario, aligned with the assumptions of the RNC2050.

1.5 Thesis outline

The thesis is structured into 6 chapters:

1. Introduction: understanding the background and the aim of this thesis.
2. State of art: addressing the basic concepts, discussing previous long-run energy studies, their strengths, limitations and opportunities for improvement.
3. Methods and Data: detailing the data sources, the estimations, the assumptions and the model.
4. Results: presenting the outputs of the model, which are the BAU and Optimistic scenarios.
5. Discussion: interpreting the results, comparing them with the results of the RNC2050, reflecting on their significance and discussing the broader implications for policy, society and future research
6. Conclusion: summarizing the key findings and contributions of the work and providing recommendations for future modelling and policy design.

1.6 Contribution of this thesis

The aim of this thesis is to build a combined energy - economy model that incorporates the insights of exergy economics at the national scale, developed upon the thesis of (Fidalgo Pinto Veloso da Silva et al., 2020). Their work provides the starting basis for the structure of the model, which has been expanded and updated. For example, some of the improvements made are the incorporation of evolving end-use energy efficiencies and the introduction of capital depreciation, allowing for a more realistic representation of long-term investment dynamics. The model also relies on core assumptions from the RNC2050, such as regarding sectoral electrification pathways, and from the MEET2030, extending the temporal scope to 2050 with a decarbonization horizon.

This modelling effort addresses several of the limitations observed in the RNC2050, integrating exergy conversion and aggregate efficiency into the macroeconomic framework, allocating exergy across sectors, energy carriers and particularly to end-uses, estimating Total Factor Productivity dynamically as a function of exergy efficiency. Moreover, GDP evolution is modelled endogenously, using capital, labour and TFP, which depends on aggregate efficiency, as primary inputs. The outcome is the definition of two different scenarios: a Business-as-Usual scenario, in which is assumed a continuation of current trends without major disruptions or breakthroughs, and a Decarbonization scenario, aligned with the RNC2050 assumptions. Then, the results of this model and of the RNC2050 are compared, showing the main differences between them and highlighting the added value of an exergy based economic perspective. The model, as both RNC2050 and MEET2050, tracks the CO_2 emissions at sectorial level, offering deeper insights into their origins and helping identify the most effective strategies for maintaining the decoupling between economic growth and emissions reduction.

2. State of the Art

2.1 The Role of Scenario Modelling in Climate and Energy Planning

Scenario modelling has become an important tool in order to develop strategies across a range of areas, including environmental sustainability and economic resilience. It is widely used by both international organisations, such as the IPCC and national institutions trying to anticipate future challenges and opportunities, simulating possible paths and assessing the implications of different policy choices at both global and national levels.

The IPCC publishes global scenarios typically every 5-7 years, as part of its comprehensive assessment reports. These scenarios are based on multiple shared socioeconomic pathways, providing data on population growth, urbanization and GDP per capita, and other variables, like greenhouse gas concentrations and technological developments. The primary aim is not only to advance climate scientific understanding, but also to provide information and actionable indications to governments and civil society on how different actions could shape future climate outcomes.

At European level, there are also several models providing bases for policy strategies, such as primes and times (Capros et al., 2014). These models are typically bottom-up, technology-rich tools used to assess energy and environmental impacts in different regulatory and technological contexts.

At national scale, Portugal, like many other countries in Europe, established a project in order to make long-term scenarios, in line with the goals of the Paris Agreement, in the context of decarbonisation targets for 2050. The Roteiro para a Neutralidade Carbonica, RNC2050, was published in 2019 and it can be considered Portugal's flagship roadmap for achieving carbon neutrality. It offers a structured vision of future sectoral transformations and policy pathways, with the objectives of the Paris Agreement and the European Green Deal.

2.2 Portuguese Climate Roadmaps: RNC2050 and MEET2030

The RNC2050 constitutes a flagship initiative in the framework of Portugal's climate policy, defining the pathways through which the nation can achieve net-zero greenhouse gas emissions by 2050. The roadmap was prepared using an inclusive methodology with the participation of fundamental institutions, like INE and APA, and encompassed a broad consultative process with various stakeholders in society. Its primary objective was to outline a deep decarbonization path for the future, which also was economically feasible and technically sound, whilst at the same time helping to remedy social injustices, regional disparities and strengthening the economic system. The concept is based on creating a bold decarbonization plan that is consistent with the climate neutrality goal. The plan is focused on the combination of various energy resources for all sectors of the economy: energy production, transport, building, industry, agriculture, and forestry, aiming to reduce emissions by more than 85% until 2050 compared to 2005 emissions. The rest of the emissions will be neutralized by promoting the natural carbon sinks, such as forests and soils, through land that is managed in a more effective way. Building the scenario included simulating various deep tech changes and behavioural changes such as the increase of clean power, electrification of end-uses, energy conservation, circular economy efforts, and sustainable land and transport planning. Besides that, it considered the expected demographic and economic changes, referred to as using national statistics and population projections. In addition to this, RNC2050 has also traced out the future scenario and have looked at its impact on various areas like job creation, investments and geographical growth to match the ambitions of creating a green future while at the same time catering socio-economic necessities. The process of formulating the strategic plan enabled the preparation of sectoral action plans that indicated core steps and mitigation features for sustainable development and resilience towards climate change for each business sector. Despite its strengths, RNC2050 exhibits several limitations, such as the adoption of pre-defined GDP trajectories, exogenously determined, rather than deriving them from economic-energy system feedback, and then the absence of exergy analysis, just relaying the analysis on primary and final energy consumption.

These gaps are significant, especially considering recent findings that emphasize the physical foundations of economic activity. (Santos et al., 2021) showed for Portugal that changes in aggregate final-to-useful exergy efficiency are closely correlated with changes in TFP, suggesting that it can be largely explained by technological and thermodynamic improvements in the energy system. Significant research was also done by (Serrenho et al., 2014, 2016) on the relationship between GDP and useful energy in Portugal and in numerous other European countries. At the national scale, their findings indicated that over a time span of over 150 years, from the mid-19th to the beginning of the 21st century, the ratio of GDP to useful energy was remarkably constant. The persistent uniformity evidenced over a long period of time supports the idea that economic growth basically depends on thermodynamic efficiency since it accentuates a strong correlation between an economy's ability to produce output and the availability and efficient use of energy services. At the European level, Serrenho et al. analysed the interrelationship between useful exergy consumption change and GDP with data on 14 nations for the period 1960-2009. The ratio of useful exergy to GDP had essentially zero variability according to aggregate data but in analysis was revealed to be dominated by use of high-temperature heat, particularly in industry, that has high energy intensities but may not be proportionally captured in value-added terms. As a matter of fact, the ratio of GDP to useful energy consumption seemed to be invariably constant from nation to nation if these high-temperature end-uses are excluded from contemplation.

Another major contribution to Portuguese scenario analysis is the MEET2030 project (Alvarenga et al., 2017), representing an important step towards coupling energy systems to economic dynamics. Unlike traditional models, MEET2030 explicitly incorporates exergy into its energy-economic system and establishes a direct relationship between GDP evolution, aggregate exergy efficiency, and capital-labour inputs. The project explores three alternative pathways for Portugal up to 2030, each of which includes a specific narrative concerning the future of the energy system:

- The Ostrich scenario is a pathway of minimal intervention in which current trends persist with minimal aspiration for energy efficiency or carbon reduction projects. It presumes the absence of policy introduction and weak societal compliance in adhering to sustainability goals.

- The Lynx scenario is a more active scenario with moderate technology innovation, policy response, and changes in behaviour. It involves increases in energy efficiency and an evolution toward cleaner energy sources.
- The most ambitious is the Lynx+ scenario, which was born from a rebound effect in the Lynx scenario, i.e. higher GDP means higher CO2 emissions. Lynx+ entails deep decarbonization through extensive structural transformation of the economy. The variables taken into account are the electricity mix and the possibility of carbon sequestration through processes that enhance ecosystem services.

These contexts provide a sophisticated assessment of how Portugal might achieve its energy and climate goals through differing levels of ambition. But the time perspective of MEET2030 is short: as all projections end in 2030, the model is not able to examine if these pathways are adequate to achieve carbon neutrality in 2050, or account for long-term interactions between energy systems, technological change, and macroeconomic evolutions. Thus, although MEET2030 is a useful tool for short- to medium-term planning, it does not address the necessity for complex, long-term models that are capable of assessing sustainability transitions across dozens of years.

2.3 The Energy-Economy Nexus: From Energy Inputs to Economic Output

The climate visions outlined in plans such as RNC2050 and MEET2030 are based on the assumption that economic growth and the growth of energy systems can proceed hand in hand, but these studies fail to incorporate the feedback loops between these dimensions into their calculations. A key factor typically absent from standard macroeconomic models is the contribution of energy – not only in terms of availability, but also quality and efficiency – in influencing economic productivity. Conventional specifications typically express GDP as a function of capital (K) and labour (L) and a residual total factor productivity (TFP). The most widely used formulation is the Cobb-Douglas production function:

$$GDP = TFP * HL^{\alpha} * K^{1-\alpha}$$

where α is the elasticity parameter.

In this framework, most of the economic growth is explained by the TFP, which is often treated as a residual, representing, as Abramovitz said, a measure of our ignorance, accounting for everything not explained by capital and labour, including technological innovation, the exergy concept and institutional factors, such as the education of the population. But this residual hides the profound physical reality: economic activity is thermodynamically constrained and depends on the capacity of the energy system to provide useful work. Recent studies attribute part of what is attributable to TFP to endogenous changes in energy efficiency, i.e. the final useful exergy efficiency of the energy system.

Improvements in the final to useful chain, achieved through electrification, better conversion technology or more efficient end uses, increase the effective energy for production and thus affect GDP. By incorporating exergy and its conversion, it is now possible to explain how technological and structural changes in the energy system affect economic growth from within the system itself. This allows for a more realistic explanation of TFP, from an unspecified residual to a measurable physical change function and establishes an endogenous connection between energy structure, energy efficiency and macroeconomic performance. Such a framework is essential for determining the feasibility of long-term decarbonisation strategies and for balancing economic and climate policy in accordance with physical constraints and actual technological potential.

2.4 Exergy, Efficiency, and Macroeconomic Integration

A key concept to clarify is the aggregate exergy efficiency, which is defined as the ratio between useful exergy and final exergy. It is a good measure to capture the effectiveness of the entire energy system and represent an indicator for technological progress, since improvements in this efficiency reflect better use of energy carriers, transitions to electrification, and adoption of more efficient technologies.

In practice, exergy modelling involves the disaggregation into: primary exergy, the one in its natural form, like crude oil and sunlight, then final exergy, the one available to end-users after transformation and distribution, like electricity and diesel, lastly useful exergy, the portion that is actually converted into services, like heating and lighting.

These are further categorized into sectors, energy carriers and end-uses, which enables detailed tracking of thermodynamic losses and efficiency gains.

Thanks to the work of (Felicio et al. 2017), historical exergy balances and efficiency shares have been computed for Portugal and can now be used to connect energy system performance to economic variables. This allows models to endogenously link TFP to final to useful exergy efficiency, thus integrating energy quality directly into macroeconomic forecasts.

3. Model Structure and Data Assumptions

This chapter delineates the architecture of the model constructed to investigate two alternative future scenarios in Portugal until the year 2050: a Business-as-Usual scenario and an Optimistic scenario corresponding with the long-term objectives and assumptions of the RNC2050 roadmap. The model functions in yearly time steps and merges demographic, economic and energy-exergy dynamics into a single framework that ultimately provides projections of CO_2 emissions and carbon intensity through time. The model can be roughly broken down into three parts that are interconnected. The first part deals with the task of establishing the contribution of human labour (HL) to GDP. The second part is about the calculation of capital, being the result of the previous year's capital, the current year's investment and depreciation. The last section is dedicated to the energy system, where the exergy is allocated across sectors, carriers and end uses, thus making it possible to register the efficiencies and the consequent emissions. All these parts are very much interconnected, which means that the alterations in one area will influence the whole system, creating a rich and realistic simulation of Portugal’s evolution.

3.1 Human Labour: Structure and Assumptions

The contribution of human activity to the economy is represented by the Human Labour, which measures the total number of hours worked by all the engaged individuals in the economy, integrating demographic and labour market characteristics. For the computation of the HL, the following formula is used, in which every term represents a different part of the socio-economic structure:

$$HL_t = WAP_t * LFPR_t * (1 - u_t) * H_t$$

- Working age population (WAP) represents the part of the population that is generally considered suitable for work, and it varies from 15 to 64 years. The BaU scenario follows the central projection of (INE, 2020), with the WAP declining from 6.5 million to 5.5 million. For the Optimistic Scenario, it is appropriate to follow the roadmap, which is based on (INE, 2017). However, to improve the accuracy, the same upper scenario is considered, but using the most updated data, (INE, 2020). According to this projection, the WAP decreases from 6.5 million to approximately 6 million for the same time period.

- Labour Force Participation Rate (LFPR) indicates the share of the working age population who are currently engaged in the labour market, either employed or actively seeking for work, and it can be seen as the ratio between the Labour Force and Working age Population. It is a key indicator of social inclusion and workforce mobilization, and the historical data used are provided by the International Labour Organization, using the ILOSTAT data explorer, and by the INE database up to 2024. In the BaU scenario, it increases from 0.792, last data available, up to 0.85 in 2050. The optimistic scenario, on the other hand, reached 0.9, assuming inclusive polices and structural improvements in workforce participation.

- Unemployment rate (u) measures the percentage of the active workforce that do not have a job, but it is still searching for it, thus it takes into account the inefficiencies of the labour market. Historical data comes from the INE database up to 2024 and in the BaU scenario this term is assumed to maintain the same value as it was in 2024, i.e. 6.4%. Instead, in the optimistic scenario the unemployment rate will decrease up to 5 % by 2050, the 2023 record global average stated by (United Nations, 2024).

- Average Hours Worked by an engaged individual (H) gives an idea of the labour intensity per worker. Historical data from Penn World Table database outlines the baseline up to 2018 and then for the BaU scenario the last historical year value is kept constant, i.e.1864.5 hours worked per year, while for the Optimistic scenario it gradually decreases up to 1450 hours per year in 2050, resulting from 8 hours of work per day, 4 days of work per week and 45.3 weeks of work per year, showing a transition to a 4-day workweek.

Taken together, these components construct a dynamic representation of human productive effort. HL not only serves as a direct input into GDP, but also as a socio-technical indicator that mirrors broader societal and institutional evolution.

3.2 Capital Accumulation and Investment in Renewables

Capital, along with human labour, is a major factor in the economic output in the model. It is calculated through a stock-flow mechanism, where annual changes in capital stock depend on investment and depreciation:

$$K_{s,t} = K_{s,t-1} + I_{s,t} - D_{s,t}$$

To increase accuracy, the capital (K), investments (I) and depreciations (D) are divided into sectors. Thus, the model is able to reflect the characteristics of each sector and show how the capital accumulation is linked to the historical economic structure of the region. All historical data for capital, investments and depreciation are obtained from the Eurostat database.

For the Business-as-usual scenario, the yearly investment in a sector is calculated by the product of the average investment-to-GDP ratio, historically observed from 2000 to 2022, and the GDP of the previous year. While for the Optimistic scenario, the RNC2050 assumptions are followed, since it gives yearly investments divided by sectors. However, to track the more rapid diffusion of the renewable energy sector, the cost of the extra renewable capacity, defined as the difference between the renewable capacity in the Optimistic and the BaU scenarios, is subtracted from the total investment, meaning that this portion of the investment is imposed and forced to be spent to meet the roadmap targets, and it can be considered as an extra or additional investment dedicated to renewable energy.

To get the yearly depreciation in a sector, the average of depreciation-to-capital ratio, which is also recorded from 2000 to 2022, is applied to the previous year's capital stock for both the scenarios.

3.3 Renewable Energy Costs and Installed Power Capacity

Concerning costs of new capacity for renewable energy, historical data have been taken from (IRENA, 2024) and it is assumed that they will follow their recent declining trend in the future. However, the decline here is supposed to be exponential until a minimum limit is reached after which the prices stay constant. For hydrogen, future projections are directly taken from (IRENA, 2020). Such trends, for both the BaU and the Optimistic cases, are taken into account, Table 3.1.

	Global average PV solar [Euros/GW]	Global average Onshore Wind [Euros/GW]	Global average Offshore Wind [Euro/GW]	Global average Battery Storage [EUR/GWh]	Global average Hydropower [EUR/GW]	Hydrogen Alkaline [EUR/GW]
2010	4672800000	1999360000	4759920000	2209680000	1283920000	
2011	4006640000	1977360000	5451600000	1848000000	1265440000	
2012	3050080000	1860320000	4776640000	1760000000	1352560000	
2013	2676960000	1921040000	5098720000	1422080000	1529440000	
2014	2419120000	1851520000	5368880000	1496000000	1401840000	
2015	1839200000	1681680000	5384720000	1358720000	1540880000	
2016	1672880000	1685200000	4239840000	1012000000	1826000000	
2017	1446720000	1686960000	4788960000	660000000	1874400000	
2018	1236400000	1600720000	4684240000	616000000	1468720000	
2019	1021680000	1518000000	4684240000	281600000	1806640000	
2020	896720000	1365760000	3753200000	264000000	1892880000	880000000
2021	836000000	1294480000	3177680000	249040000	2081200000	856533333
2022	799040000	1163360000	2785200000	315040000	2686640000	833066667
2023	667040000	1020800000	3060640000	240240000	2469280000	809600000
2024	522532765.2	1065558823	2464000000	156988988.6	2469280000	786133333
2025	449748118.9	1013590906	2791572730	128531712.9	2469280000	762666667
2026	387101793.4	964157493.8	2655426121	105232866.1	2469280000	739200000
2027	333181601.2	917134978	2525919461	86157383.7	2469280000	715733333
2028	286772061.8	872405777.3	2402728915	70539699.64	2469280000	692266667
2029	246827001	829858045.5	2285546443	57753021.41	2469280000	668800000
2030	212445968.5	789385391	2174079028	47284174.71	2469280000	645333333
2031	182853939.7	750886611.2	2068047942	38713007.97	2469280000	621866667
2032	157383844.4	714265439	1967188054	31695530.17	2469280000	598400000
2033	135461530.2	679430302.5	1871247161	30000000	2469280000	574933333
2034	116592819.6	646294095.6	1779985360	30000000	2469280000	551466667
2035	100352369.8	614773960.7	1693174449	30000000	2469280000	528000000
2036	100000000	584791080.8	1610597357	30000000	2469280000	504533333

2037	100000000	556270483.2	1532047597	30000000	2469280000	481066667
2038	100000000	529140851.6	1457328754	30000000	2469280000	457600000
2039	100000000	503334347.8	1386253992	30000000	2469280000	434133333
2040	100000000	478786442	1318645587	30000000	2469280000	410666667
2041	100000000	455435751.7	1254334483	30000000	2469280000	387200000
2042	100000000	433223887.9	1193159868	30000000	2469280000	363733333
2043	100000000	412095309.6	1134968775	30000000	2469280000	340266667
2044	100000000	391997184.2	1079615694	30000000	2469280000	316800000
2045	100000000	372879255.9	1026962216	30000000	2469280000	293333333
2046	100000000	354693720	976876677.5	30000000	2469280000	269866667
2047	100000000	337395103.2	929233839.7	30000000	2469280000	246400000
2048	100000000	320940149.8	883914570.6	30000000	2469280000	222933333
2049	100000000	305287714	840805548.3	30000000	2469280000	199466667
2050	100000000	290398656.5	799798977.8	30000000	2469280000	176000000

Table 3.1 – Renewable energies costs per GW

Looking at Figure 3.1, the trajectory of renewable technology costs can be seen. A clear decline is observed for most technologies up to a certain point where most of them reach a minimum. The only exception is represented by hydroelectric power, since the historical trend shows an increasing behaviour and for this reason, it has been assumed to maintain the same cost of the last data available. The cheapest technology for most of the time is the solar photovoltaic, while at the end of the study period the most expensive after hydropower is the offshore wind, reflecting its technical and operational demands. Hydrogen costs represent the installation of an alkaline electrolyser, and they drop linearly up to 2050, becoming the 2nd cheapest technology.

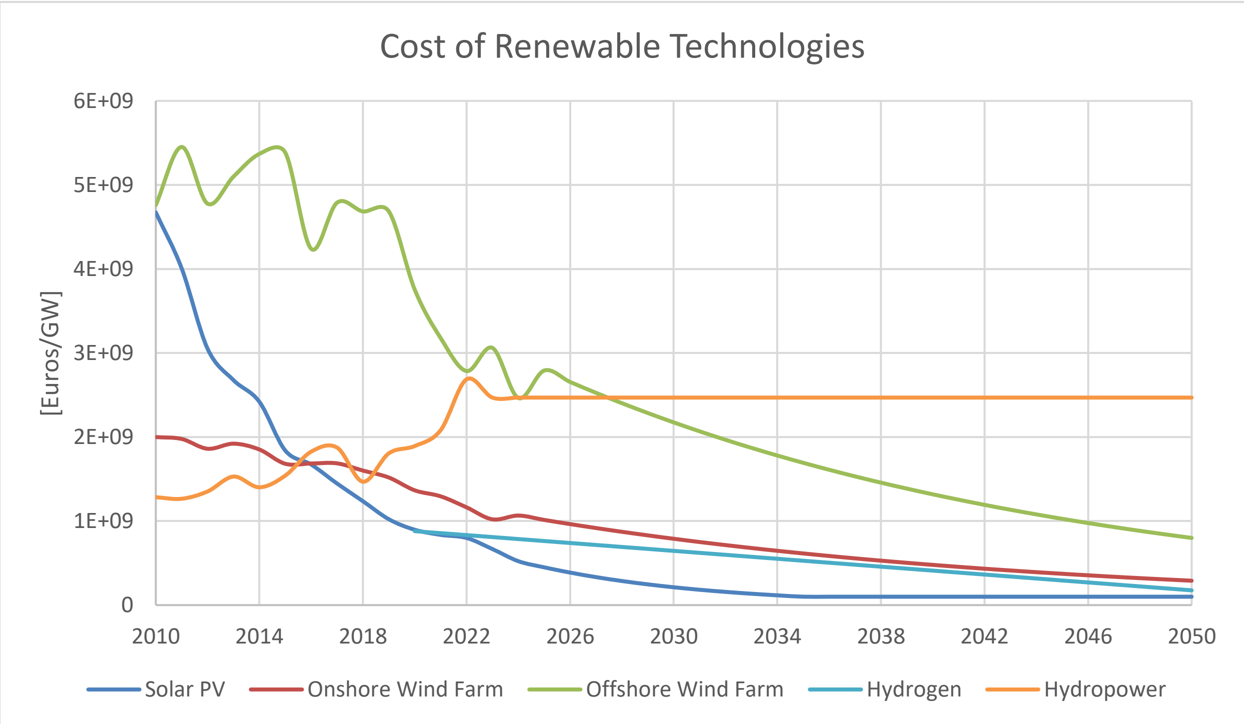

Figure 3.1 - Evolution of the renewable technology costs

The data on installed renewable capacity are derived from (IRENA, 2025). The growth trend in the installed capacity of renewables in the BaU scenario is the same as in the past. In contrary, the Optimistic scenario corresponds to the goals of RNC2050 which propose a major acceleration of installing solar, wind and other renewable sources and the implementation of hydrogen.

To reflect these dynamics in the macroeconomic model:

- The price of supplemental renewable capacity (Optimistic minus BaU) is calculated annually.
- This additional investment is subtracted from the sectoral investment baseline to avoid double counting, thus being consistent with total investment with no overestimation.
- In the BaU scenario, renewable investments are by default part of historical investment-to-GDP ratios and, hence, no special treatment is necessary.

Such a method guarantees that the energy transition is not only financially explicit but also macroeconomically consistent within the overall capital formation model.

3.4 Total Factor Productivity and GDP Computation

While in neoclassical frameworks, capital and human labour are the two traditional pillars of GDP, Total Factor Productivity is the key to recognizing the extent of technology progress and systemic efficiency. Instead of taking TFP growth as exogenous, this model adopts the formula from the ExergyX project (Santos et al., 2021) which fundamentally connects TFP with the aggregate efficiency:

$$TFP \propto AggEff$$

By defining TFP as a function of how efficiently final exergy is converted into useful exergy, which is much closer to economic value, the model allows for a more endogenous and thermodynamically grounded representation of technological progress. As mentioned above, the aggregate efficiency is calculated yearly based on the distribution of exergy among sectors, carriers and end uses and the related efficiencies.

GDP is then estimated as a function of HL, K and TFP, thus linking economic growth with energy-system changes, employing the Cobb-Douglas formula mentioned in (Section 2.3), in which the elasticity parameter is 0.7, indicating that HL is responsible for 70% of the GDP and K for 30%.

3.5 Energy-Exergy Allocation and Efficiency Estimation

The final component of the model deals with the energy system, tackled specifically by taking an exergy-based approach. The model takes the form of a series of nested steps to follow the chain of exergy allocation. Firstly, using (Serrenho et al., 2014), total useful exergy demand is directly proportional to GDP, in fact 1 billion of Euro of GDP = 1000 TJ of total useful exergy. From 1856 to 2009, the relationship between these two variables remained stable, based on data for Portugal expressed in euros at 2010 constant prices, therefore it is assumed valid also for this analysis, even if it could change in future, applying polices different from the past. The total useful exergy is subsequently converted into total final exergy using the aggregate efficiency of the same year and then distributed between economic sectors (industry, transport, residential, services, agriculture/forestry/fishing, and energy own use), energy carriers (coal, oil, gas, renewables, electricity, waste, etc.), and finally end uses (e.g., high-temperature heat, low-temperature heat, mechanical drive, etc.). Historical information for these shares is derived from IEA statistics. In the BaU scenario:

- Sectoral exergy shares of final exergy follow historical trends 1960-2022, relying on their long-term linearity.
- Carrier shares and end-use distributions are obtained for 2012-2022, since post-crisis restructuring.
- Carrier efficiencies are also extrapolated from their historical trends 1960-2022.

For the Optimistic case, all the shares follow RNC2050 projections and assumptions, bringing huge alterations towards electrification and decarbonization. However, the end-use efficiencies are assumed to remain constant as in BaU, being respectful of the difficulty of altering device-level efficiencies radically within such a time frame. However, the shift towards more efficient and less environmental pollutant carriers has an impact on aggregated efficiency.

These assumptions and allocations allow for the calculation of annual aggregate exergy efficiency, which in turn translates back into calculation of TFP.

3.6 CO_2 Emissions and Carbon Intensity

Having final exergy by carrier from the complete breakdown, the model derives CO_2 emissions based on carrier-specific emission factors. If the electricity demand exceeds the production capacity of renewables, natural gas is used as the marginal source, generating additional emissions.

The last output that the model produces is:

- Total CO_2 emissions: embodying the environmental effect of the entire energy-economic system.
- Carbon intensity, which is the proportion of CO_2 emissions to GDP, is a metric that gauges the degree of decoupling between economic development and environmental deterioration.

The twin outputs offer a composite measure to determine the effectiveness and sustainability of transitions that have been modelled.

3.7 Model scheme

In order to provide a better understanding of the dynamics and logics of the model, the complete structure is visually represented in Figure 3.1.

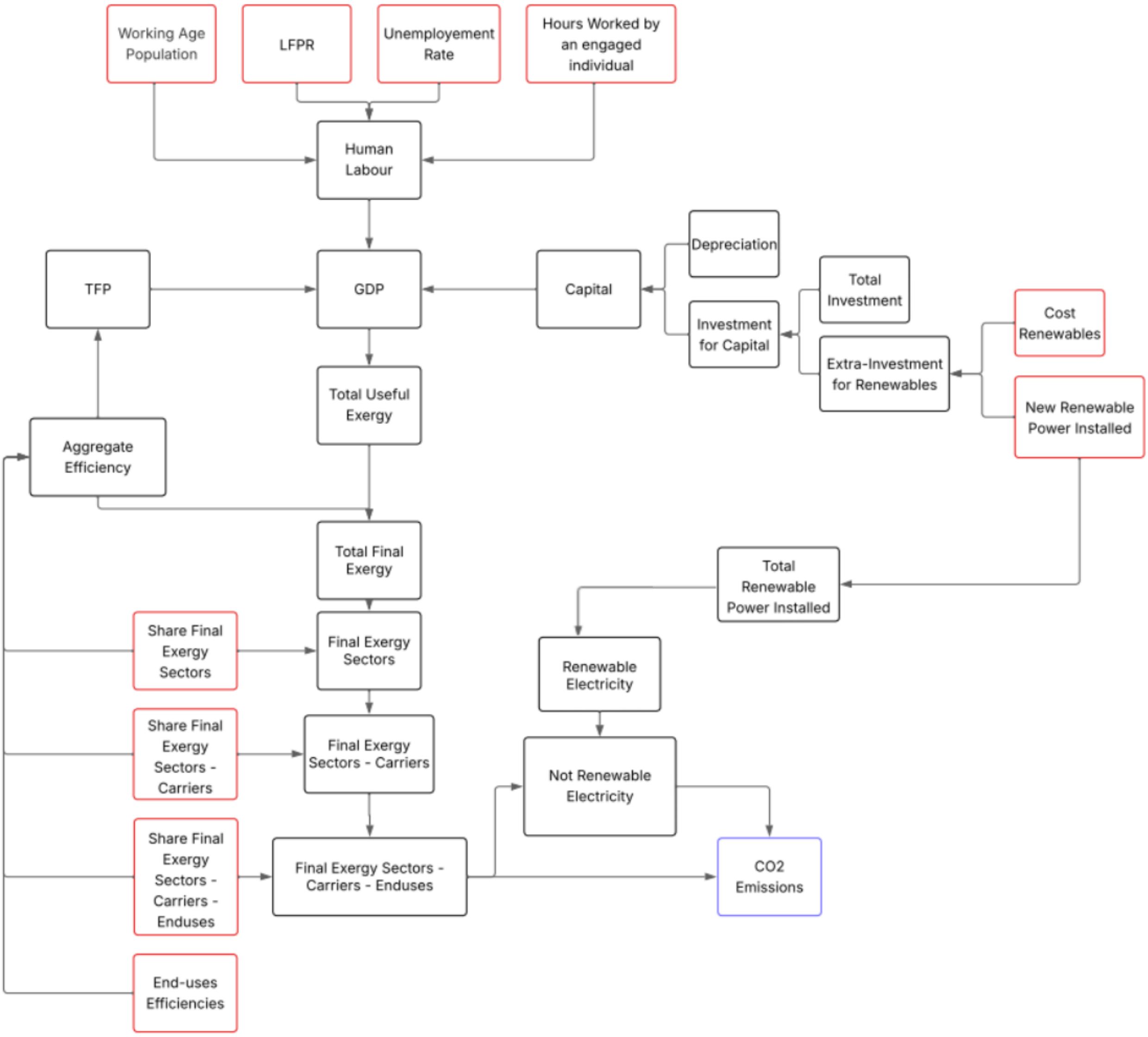

Figure 3.2 – Conceptual map of the model based on (Fidalgo Pinto Veloso da Silva et al., 2020)

The diagram gives an overview of the flows of information across the various components, describing the causal relationships and feedback loops operating between the various dimensions of the system. As can be observed in the scheme, the upper section is concerned with the socioeconomic variables, while the lower section is concerned with the energy-related variables. The interconnection between them reflects the integration between the economic and energetic subsystems, which is one of the strong points of this modelling framework. Red cells are exogenous inputs, varying with the case, while the blue cell is the model output, from which also carbon intensity can be derived, looking more in details the correlation between CO_2 emissions and GDP. Therefore, it allows us to verify if decoupling is occurring, which means whether, while GDP is growing and society should be evolving for the better, CO_2 emissions are decreasing, resulting in a reduction in environmental pollution.

3.8 Mathematical Formulation of the Model

To complement the conceptual overview, this section introduces the full set of equations that underpin the model and its internal logic. Each subsection below corresponds to a key building block of the simulation framework.

3.8.1 Human Labour

The total human labour, expressed in hours worked by all the engaged individuals in one year, is calculated as already showed before:

$$HL_t = WAP_t * LFPR_t * (1 - u_t) * H_t$$

The subscript t indicates the annual variability.

3.8.2 Capital Stock

Capital stock evolves annually as the sum of past capital stock, current investment and depreciation and they are usually measured in billions of euros:

$$K_{s,t} = K_{s,t-1} + I_{s,t} - D_{s,t}$$

The subscript s indicates the different sectors taken into account and for the BaU scenario each the investments are computed as:

$$I_{s,t} = \frac{\sum_{i=1960}^{2022} \frac{I_{s,i}}{GDP_{s,i}}}{63} * GDP_{s,t-1}$$

The number 63 represents the years of the historical data.

While depreciation is:

$$D_{s,t} = \frac{\sum_{i=1960}^{2022} \frac{D_{s,i}}{K_{s,i}}}{63} * K_{s,t-1}$$

The total capital stock is the sum across all sectors:

$$K_t = \sum_s K_{s,t}$$

This formulation enables capital dynamics based on historical structural proportions.

3.8.3 Adjustment for Renewable Investments (Optimistic Scenario)

In the optimistic scenario, renewable energy investment receives a dedicated treatment. The model computes the extra renewable capacity to be installed, compared to the BaU trajectory, usually measured in GW, then the cost, which represents the extra-investment to be made; the latter is subtracted to the investment in the respective sector.

For each renewable source i:

$$RenewableCapacity_{extra,t,i} = RenewableCapacity_{opt,t,i} - RenewableCapacity_{BaU,t,i}$$

Then the total extra-investment:

$$I_{extra,t} = \sum_{i} RenewableCapacity_{extra,t,i} * CostperGW_{t,i}$$

Where the variable $CostperGW_{t,i}$ represents the installation costs per GW of renewable energy.

This additional investment is then subtracted from the standard investment associated with the renewables sector to prevent double counting:

$$I_{adj_{s,t}} = I_{s,t} - I_{extra,t}$$

This adjustment ensures internal consistency and maintains realism in capital reallocation for accelerated energy transitions.

3.8.4 GDP and Total Factor Productivity

Economic output is modelled via a Cobb-Douglas production function:

$$GDP_t = TFP_t * HL_t^{\alpha} * K_t^{1-\alpha}$$

Where α is typically equal to 0.3.

TFP is derived from the aggregate efficiency of the same year, which will be discussed later on, and as reference the 1960 one, equal to 0.14 for Portugal (Santos et al., 2021):

$$TFP_t = (\frac{AggEff_t}{AggEff_{1960}})^{1.93} * 0.00000102 + 0.00000039$$

3.8.5 Total Useful and Final Exergy

As mentioned before, the GDP (Section 2.3), measured in billions of euros, is strictly connected with the Total Useful Exergy, measured in TJ:

$$TotalUsefulExergy_t = GDP_t * 10^3$$

Then using the aggregate efficiency, it is possible to compute the total final exergy:

$$TotalFinalExergy_t = \frac{TotalUsefulExergy_t}{AggEff_t}$$

3.8.6 Exergy Allocation and Aggregate Efficiency

The total final exergy is subsequently allocated across sectors, energy carriers and end-uses using a hierarchical share-based system.

For each sector s:

$$FinalExergy_{s,t} = ShareFinalExergy_{s,t} * TotalFinalExergy_t$$

For each carrier c:

$$FinalExergy_{s,c,t} = ShareFinalExergy_{s,c,t} * FinalExergy_{s,t}$$

For each end-use e:

$$FinalExergy_{s,c,e,t} = ShareFinalExergy_{s,c,e,t} * FinalExergy_{s,c,t}$$

Then for the computation of the CO_2 emissions, the final exergy of the different carriers is summed across the sectors since it is needed:

$$FinalExergy_{c,t} = \sum_s FinalExergy_{s,c,t}$$

The aggregate efficiency is defined as the ratio between the useful exergy and the final exergy, but since the shares and the end use efficiencies are known a priori, it is possible to compute the aggregate efficiency for the whole series:

$$AggEff_t = (\sum_s ShareFinalExergy_{s,t} * (\sum_c ShareFinalExergy_{s,c,t} * (\sum_e ShareFinalExergy_{s,c,e,t} * Eff_{c,e,t}))$$

The shares of energy consumption and end-uses efficiencies are exogenous inputs, derived from historical trends for BaU and RNC2050 assumptions for the optimistic scenario.

3.8.7 CO_2 Emissions Calculation

CO_2 emissions are computed by multiplying emission factors (EF), measured in tons of CO_2 per TJ, by the final exergy use of carriers for each of them, obtaining tons of CO_2 produced:

$$CO_2Emissions_{c,t} = EF_c * FinalExergy_{c,t}$$

If the renewable electricity supply is insufficient to meet electricity demand, the model assumes that natural gas is used to compensate. First renewable electricity is computed as following and it is measured in GWh:

$$RenewableElectricity_{i,t} = RenewableCapacity_{i,t} * CF_{i,t} * 8760$$

The capacity factor indicates how much an energy source is producing, compared to its maximum, while 8760 are the number of hours in one year. Then if $FinalExergy_{electricity,t} > RenewableElectricity_t * 3.6$, where the renewable electricity is converted to TJ knowing that $1GWh = 3.6\,TJ$, natural gas will be used to produce the remaining electricity demand and added emissions will be produced:

$$CO_2EmissionsBackup_t = \frac{\left((FinalExergy_{electricity,t} * Ineff_{primary\ to\ final}) - RenewableElectricity_t * 3.6\right)}{Eff_{NG}} * EF_{NG}$$

The formula estimates the CO_2 emissions due to backup electricity generation in, under the assumption that the electricity required not met by renewable energies is produced using natural gas. It begins with the final exergy demand for electricity and, to find the equivalent primary energy demand, multiplies it by the inverse of the efficiency of primary to final electricity conversion. This primary energy demand is then subtracted by the electricity generated from renewables. This renewable electricity is expressed in GWh and converted to TJ through a factor 3.6. The resulting difference is equivalent to the quantity of electricity that must be provided by natural gas-fired power plants. The required natural gas input is then derived by dividing through the efficiency of electricity production from natural gas and this provides the total natural gas energy input needed to meet the remaining electricity demand. The CO_2 emissions equivalent to this natural gas use are, lastly, determined by multiplying the outcome by the emission factor of natural gas. These emissions are added to other emissions to obtain the total:

$$TotalCO_2Emissions_t = CO_2EmissionsBackup_t + \sum_c CO_2Emissions_{c,t}$$

3.8.8 Carbon Intensity

The final indicator produced by the model is carbon intensity, defined as:

$$CarbonIntensity_t = \frac{TotalCO_2Emissions_t}{GDP_t}$$

This metric serves to evaluate the degree of decoupling between economic activity and environmental impact. A declining carbon intensity would indicate a cleaner growth trajectory.

4. Results

This chapter presents the main outcomes of the model, both for the Business as Usual and Optimistic scenarios, assessing how they differ depending on the assumptions made, and finally showing CO_2 emissions and CO_2 intensity for all the cases, including a comparison with the RNC2050 report. This enables to understand the potential transformation of Portugal, regarding several aspects of the economy and of the society and highlighting the policies and innovations needed to obtain certain objectives, such as climate neutrality by 2050.

4.1 Human Labour

The first important variable presented is the HL, Figure 4.1 for both the scenarios. It can be observed that the Optimistic scenario shows a more pronounced decline than the BaU scenario, reflecting the policy's implementation of a 4 days' workweek. This refers to a work-life more balanced, therefore less hours worked by each individual and labour more spread across the society with more people working actively. For this reason, even if this decreasing seems like a negative effect, it represents a trajectory in which people have more free time, symptom of happiness.

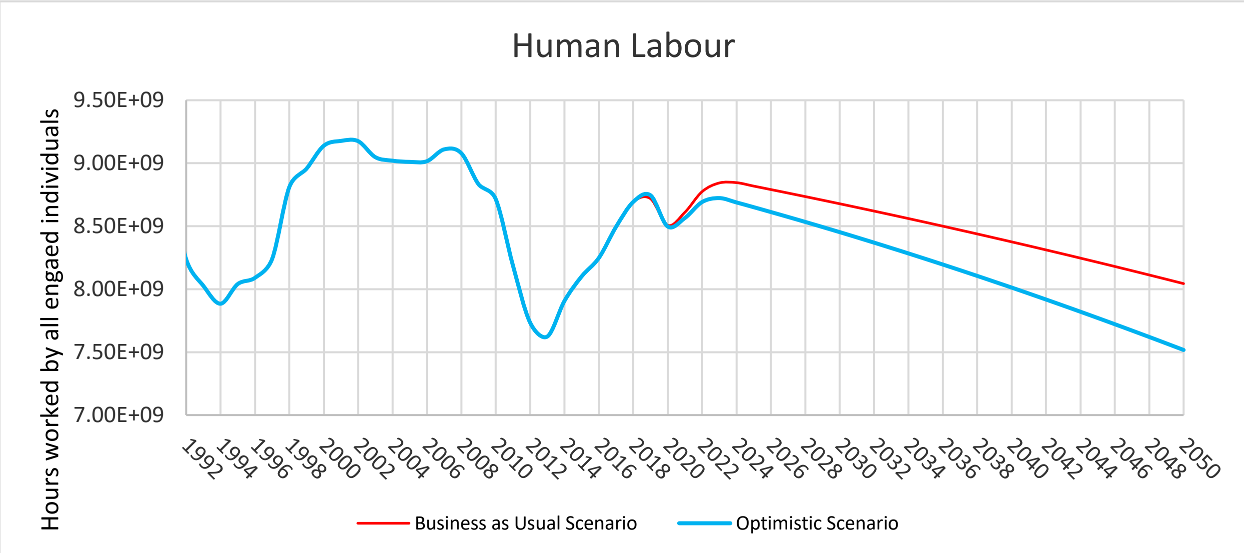

Figure 4.1 – Historical data and future projection of HL for both the scenarios

4.2 Capital Stock

The next outcome of the model is the total capital stock, which corresponds to the sum of the capitals of each sector. In this case, as can be seen in Figure 4.2, in the Optimistic scenario, total capital increases significantly over time, due to the overall rise in total investments over time. This trend diverges from the BaU scenario, since in the latter depreciation dominates new investments, causing the decreasing of total capital.

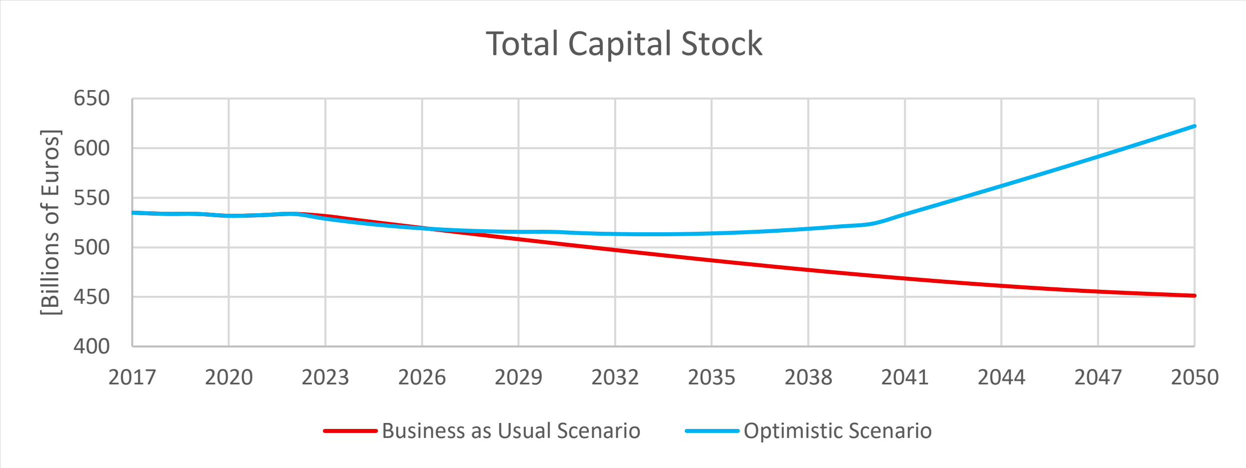

Figure 4.2 – Evolution of Total Capital Stock for both the scenarios

4.3 Total Factor Productivity and GDP

Turning towards TFP, its evolution can be observed in Figure 4.3. For the BaU scenario, a very slight upward trend can be observed, reflecting technological progress and incremental improvements in energy conversion. In contrast, under the Optimistic scenario, TFP increases much more significantly, not due to the improvements also assumed in the BaU scenario, but as result of a structural transformation of the share of final exergy across sectors, carriers and end-uses. This change mainly represents the key indicator of growing productivity and GDP alongside decarbonization.

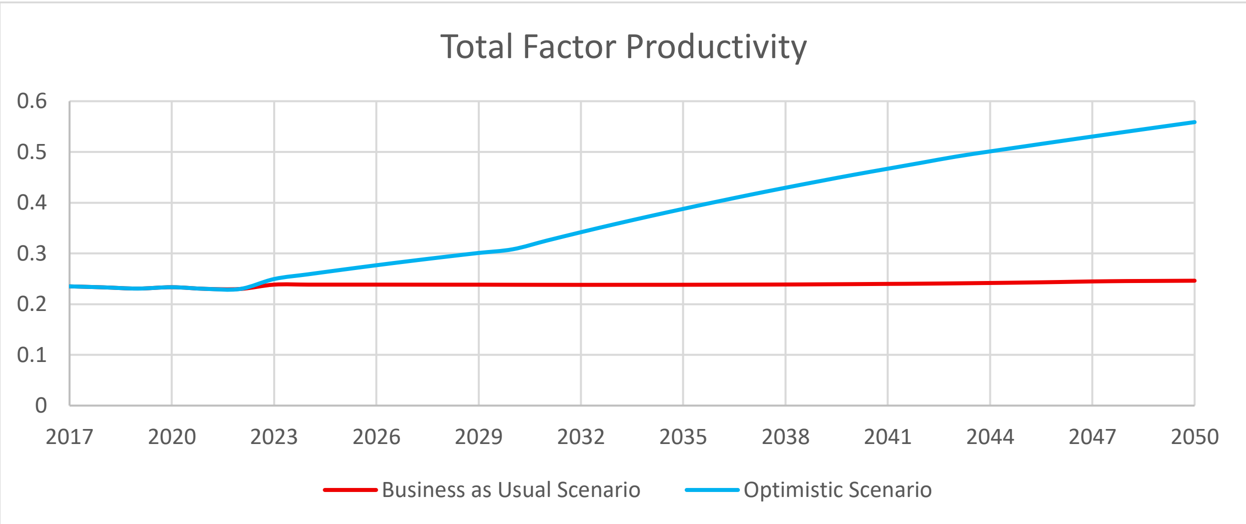

Figure 4.3 – Historical data and future projection of TFP for both the scenarios

Regarding the GDP, Figure 4.4, its dynamics varies significantly considering the scenario. In the BaU, it follows a downwards trend, going from 195 to 184 billion of euros regarding the period 2023-2050. Both the RNC2050 and the Optimistic scenario have an increasing trend, the only difference is with their scale, since GDP from RNC2050 reaches a final value of 340 billion of euros, while GDP of the Optimistic Scenario increases significantly, arriving at 850 billion of euros. In the roadmap, the GDP is treated as an exogenous variable, where initial data are given by (Banco de Portugal, 2018), while future projections rely on assumed annual growth rates. In this thesis's model, the GDP is computed as shown in Section 2.3, allowing for more complex dynamics and more variability, which explains the significant divergence between them.

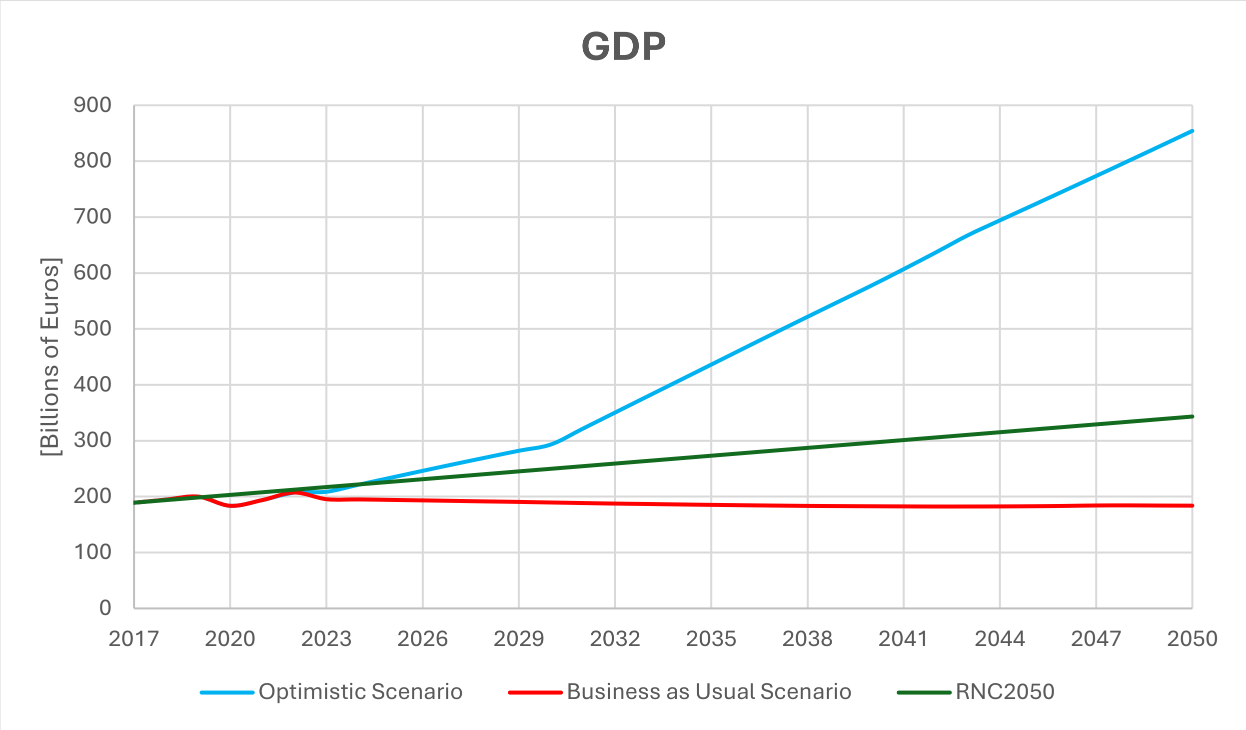

Figure 4.4 - Evolution of GDP for both the scenarios and for the RNC2050

4.4 Renewable Capacity

In Figure 4.5 it can be seen the difference in the total renewable capacity between the scenarios, which multiplied by the cost of each technology represent the extra-investment to be made. At the end of the study period, the renewable power installed in the Optimistic scenario, which coincides with the roadmap, is more than the double of the one in the BaU scenario, representing a big evolution in the Portuguese panorama.

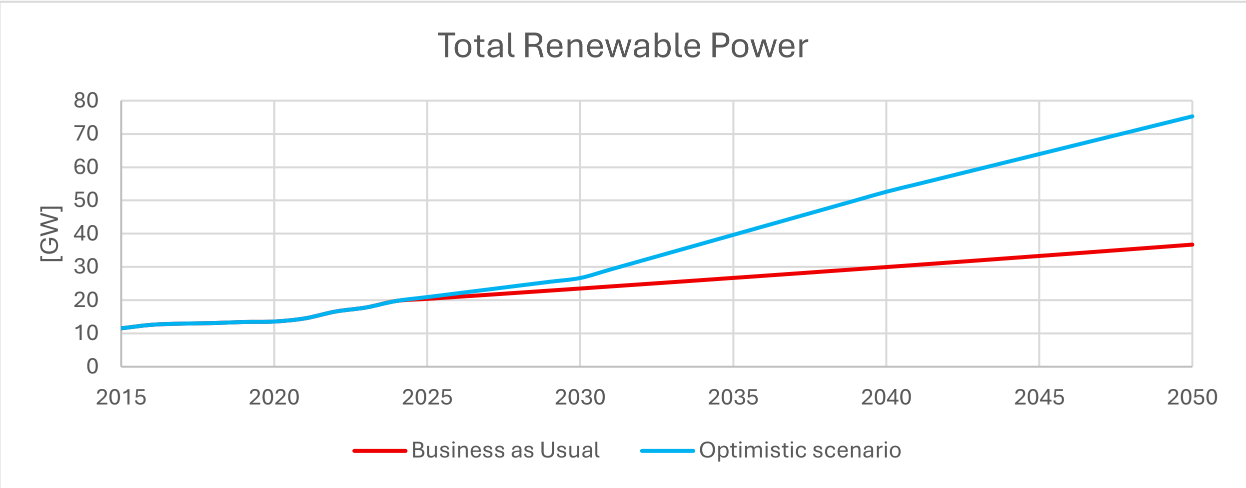

Figure 4.5 - Evolution of the total renewable power installed for both the scenarios

4.5 Total Final Exergy and Shares of Final Exergy

The evolution of the shares of final exergy across the sectors can be seen in Figure 4.6 for the BaU scenario and in Figure 4.7 for the optimistic scenario, alongside with the total final exergy required.

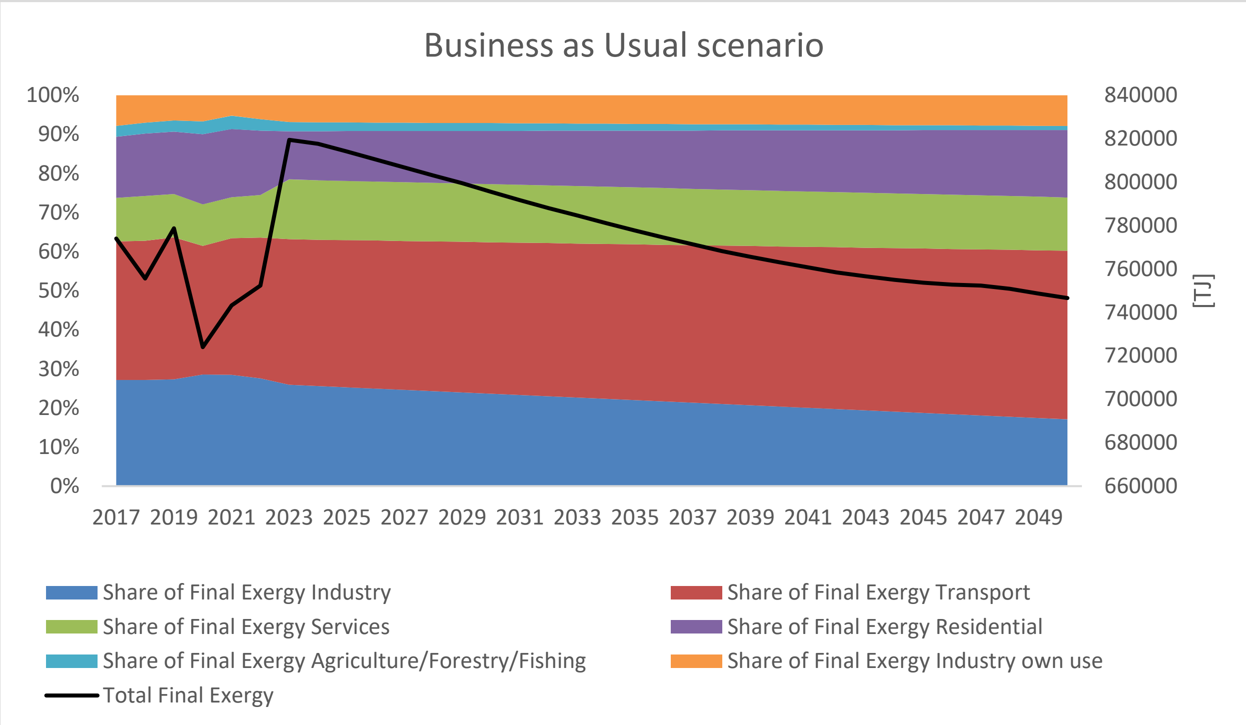

Figure 4.6 – Shares of Final Exergy across sectors and Total Final Exergy, BaU Scenario

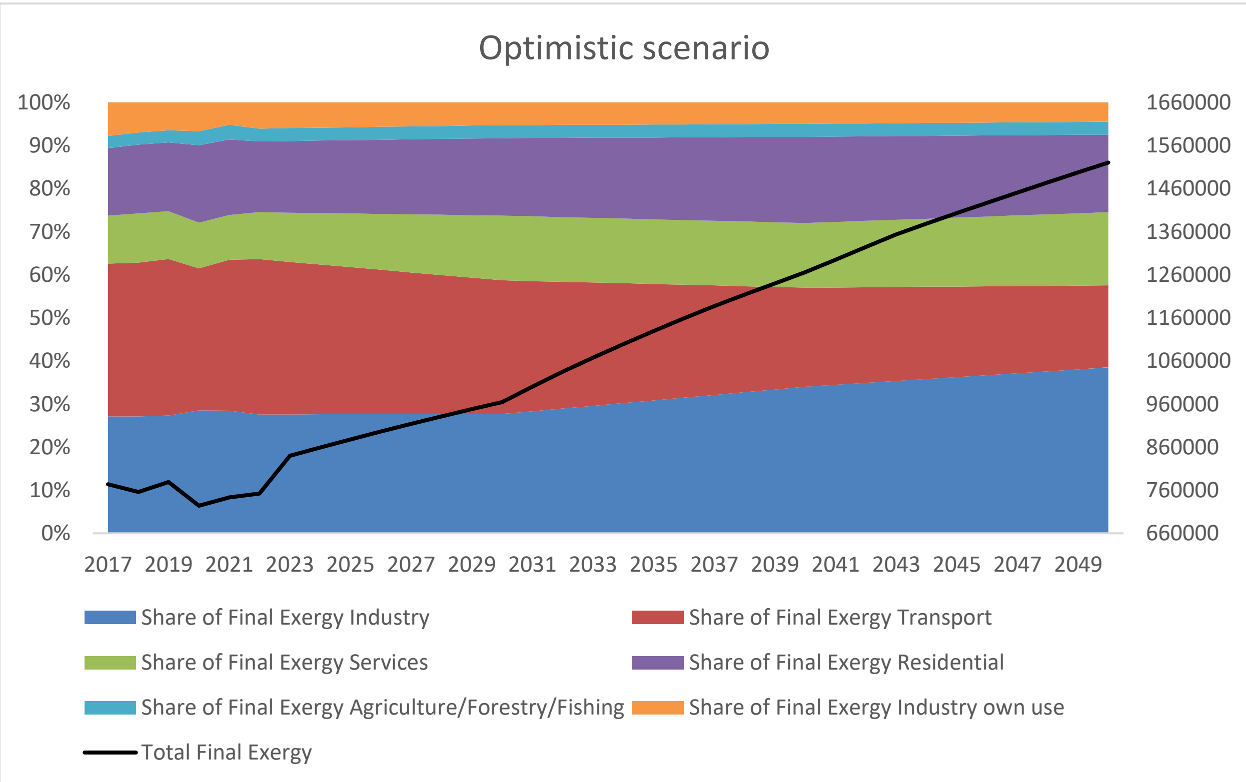

Figure 4.7 - Shares of Final Exergy across sectors and Tota Final Exergy, Optimistic Scenario

Most of the contribution for both the scenarios is given by the industry and transport sector, however they act differently considering the case. Under the BaU scenario, the share of the industry sector decreases over time, while the share of the transport sector increases, mainly because the exergy demand in transport remains almost constant, with oil representing more than 90% of the share, Figure 4.8, whereas the industry sector shows a reduction in its exergy requirement, Figure 4.9. Therefore, as consequence, the share of industry decreases compared to the transport sector.

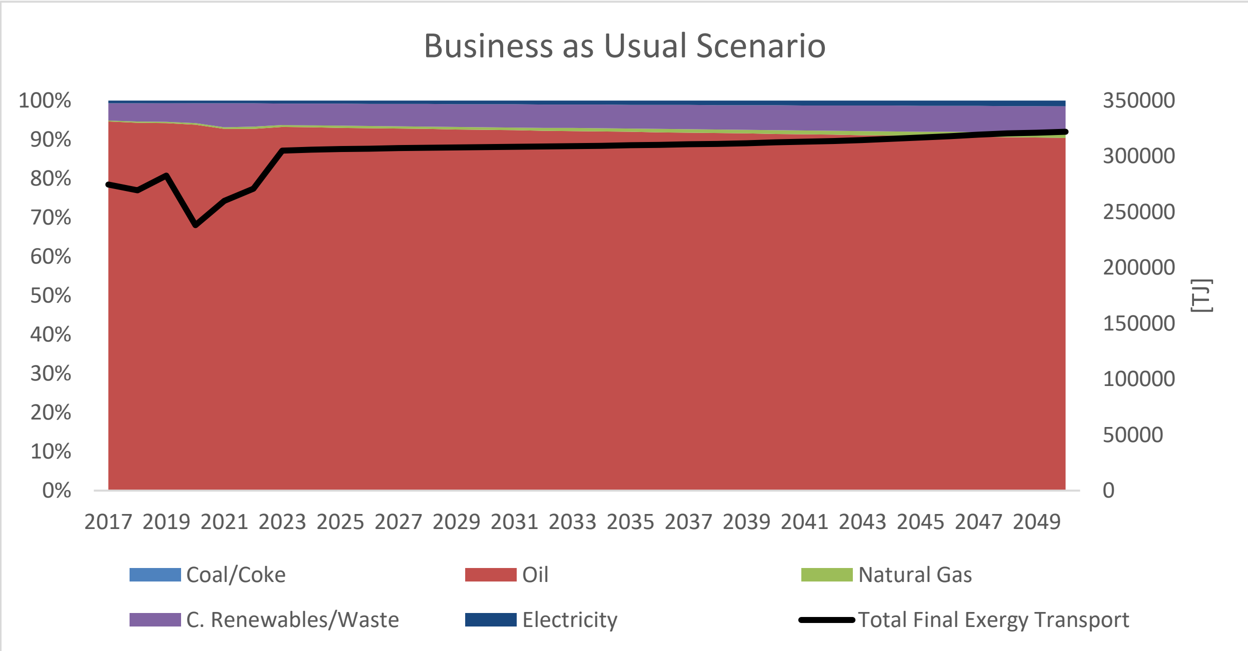

Figure 4.8 – Shares of Final Exergy in the transport sector across carriers, BaU scenario

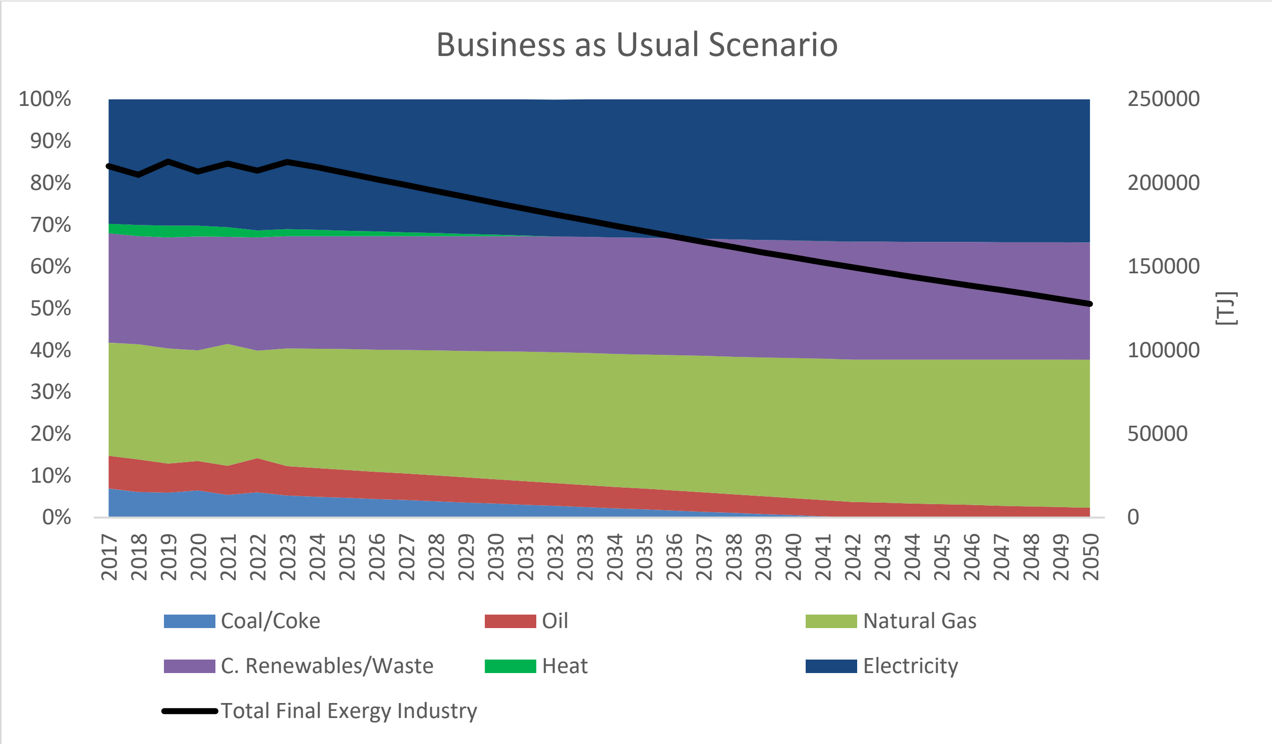

Figure 4.9 - Shares of Final Exergy in the industry sector across carriers, BaU scenario

From this last figure can also noticed that for industry natural gas is the carrier that takes a major role in future in the BAU scenario, becoming the most used. Looking at Figure 4.7 with more attention, it can be noticed that the shares of industry and transport in the Optimistic scenario act completely differently than the BaU case. Indeed, the total final exergy required increases along the years, but considering just the transport sector, Figure 4.10, it maintains mostly the same value, mainly because there is a huge electrification, with electricity and hydrogen representing more than 90% of the total share, so efficiencies grow significantly and less exergy for the same amount of work is needed.

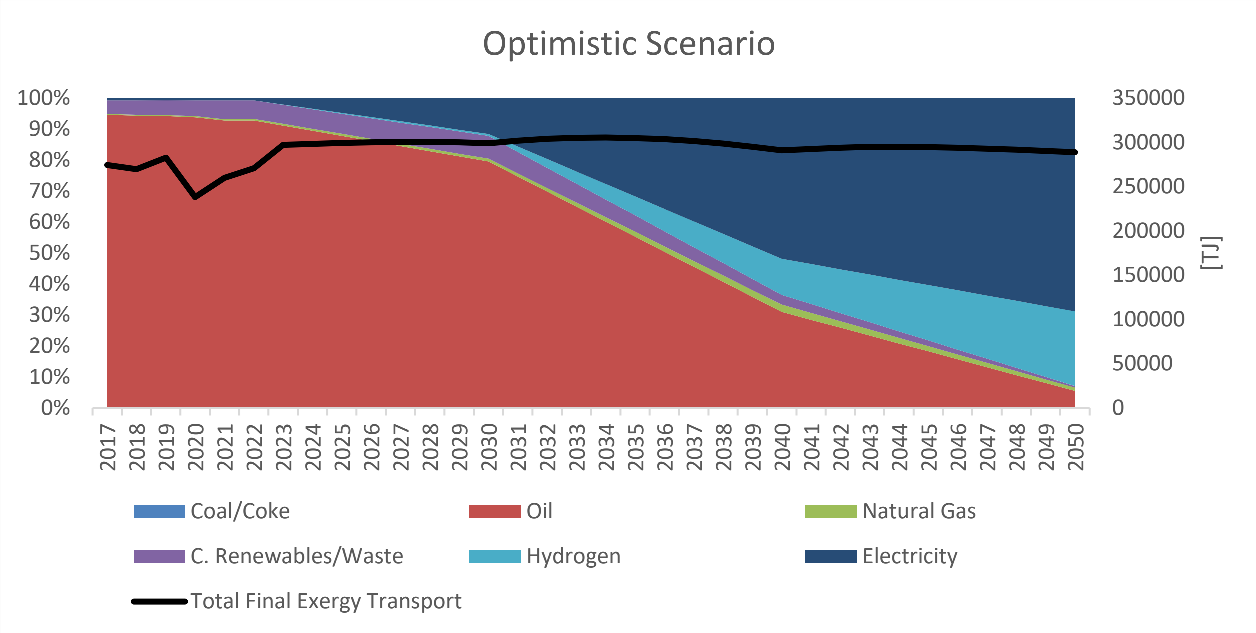

Figure 4.10 - Shares of Final Exergy in the transport sector across carriers, Optimistic scenario

Instead, for industry, Figure 4.11, electrification also takes place but not as important as in the transport sector. Electricity represents around 60% of the total share, therefore the exergy required by industry grows as well.

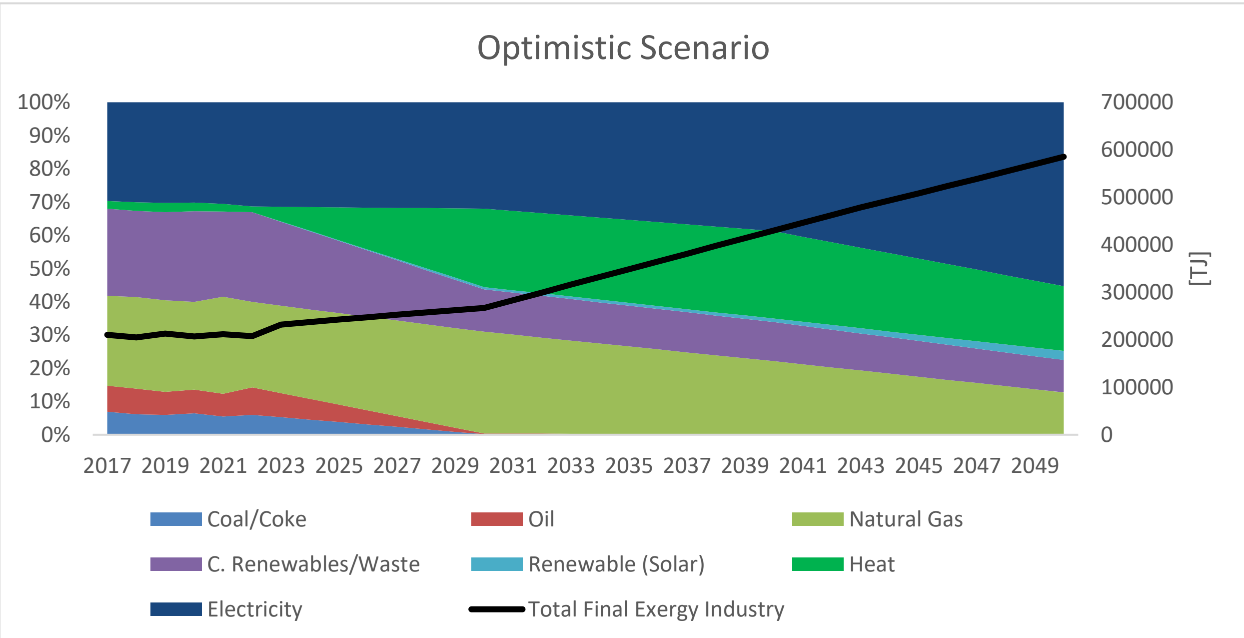

Figure 4.11 - Shares of Final Exergy in the industry sector across carriers, Optimistic scenario

4.6 Total Final Exergy - Electricity

Figure 4.12 and Figure 4.13 describe the total amount of electricity demand and its coverage by renewable sources. For both the scenarios, at the end of the study period, all the electricity is provided by renewables, but for different reasons. For the BaU, the installation of new renewable sources allows a complete coverage of the electricity needed, mostly because there is a slight decrease of its demand. While for the Optimistic scenario, the total amount of electricity required grows significantly and all of it, at the end of the study period, is covered by renewables. Therefore, 100% of the electricity is green and renewable, demonstrating the ability of policies to enable a transition toward a low-carbon energy system while strengthening its role in meeting growing energy demands.

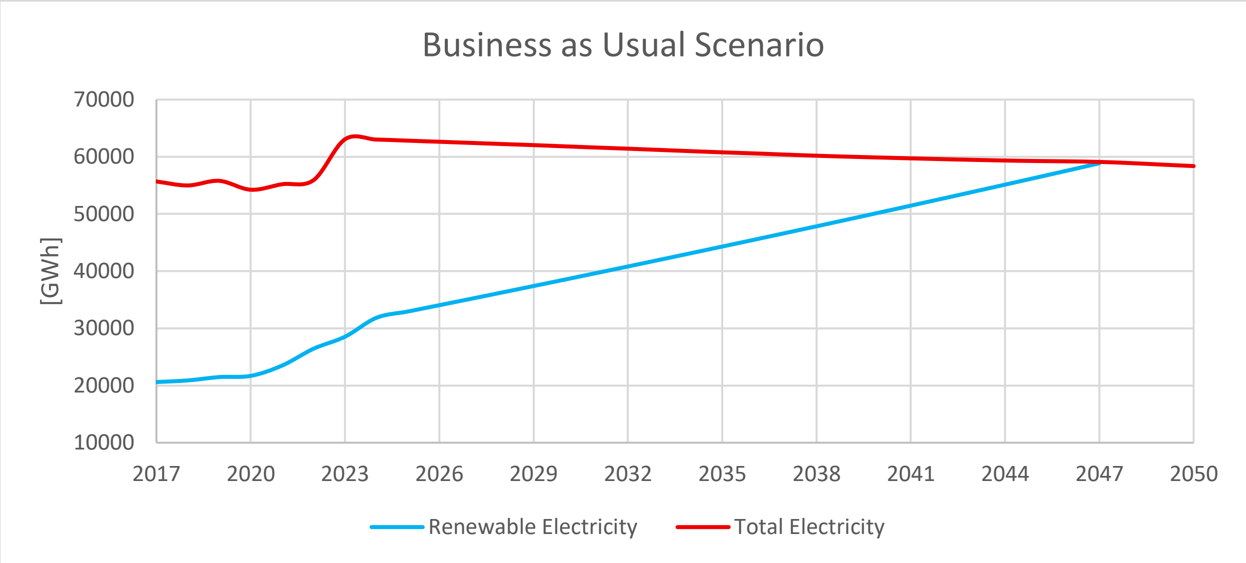

Figure 4.12 – Total Electricity Demand and Renewable Electricity, BaU scenario

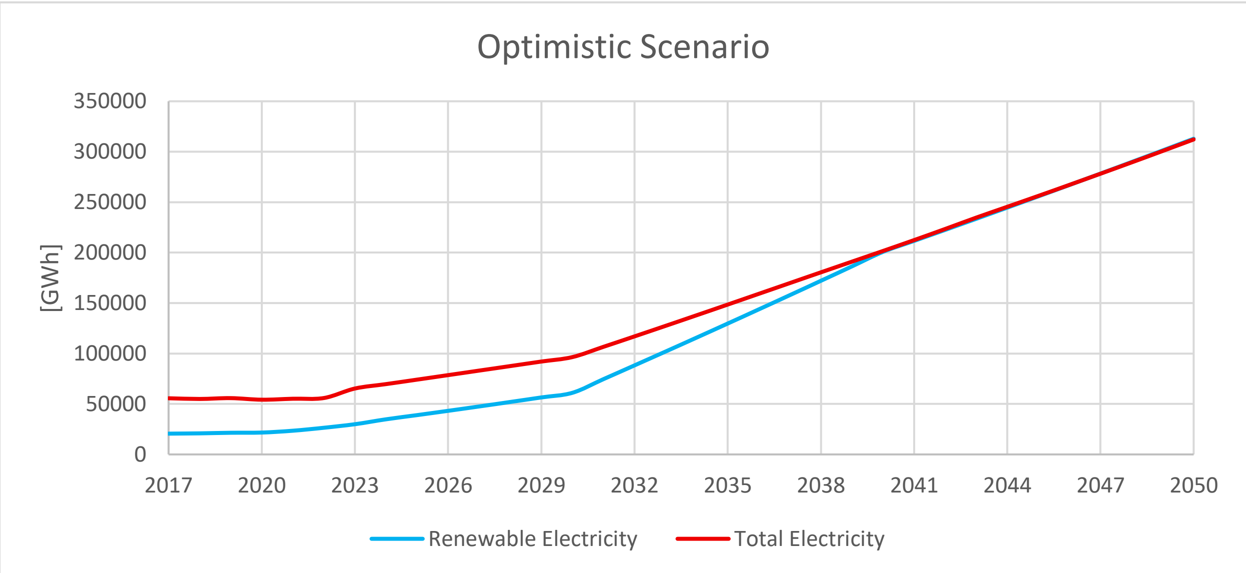

Figure 4.13 - Total Electricity Demand and Renewable Electricity, Optimistic scenario

4.7 Total CO_2 Emissions

One of the most important outcomes to show is the total amount of CO_2 emitted, Figure 4.14. The trends are similar independently for the case, since both are downwards, however none of them reaches 0 emissions. For the first period, it can be noticed a strange behaviour for the optimistic scenario, since the emissions are even higher than the BaU scenario. This is due to a fast developing of the society, with more final exergy required, not proportional to the initial amounts of investments made and that cannot be supplied mostly by renewables. After this period, the emissions decrease drastically reaching 14.43 Mton as final value. For the BaU scenario, emissions decrease as well, showing almost linearly for the whole period. However, this is caused by the fact that less final exergy is required along the years and not thanks to an electrification of the society.

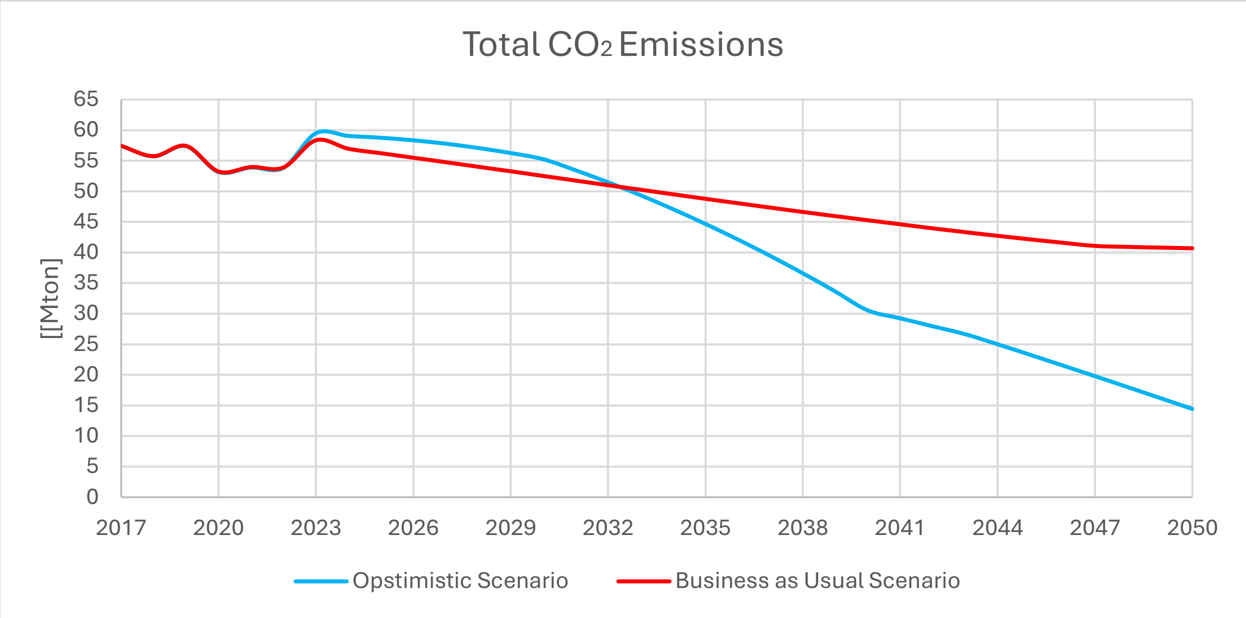

Figure 4.14 – Total CO_2 Emissions for both the scenarios

4.8 Carbon Intensity

Last to show is the carbon intensity, to investigate the relationship between CO_2 emissions and GDP, Figure 4.16. For both the scenarios the trend is downwards, however, as before, due to different reasons. For the BaU case, it is mainly because the decreasing rate of CO_2 emissions is higher than the one of GDP, while for the Optimistic case, it is evident the decoupling between the economy and the CO_2 emissions, almost reaching 0, reflecting a true transformation toward a low-carbon, high-value-added economy

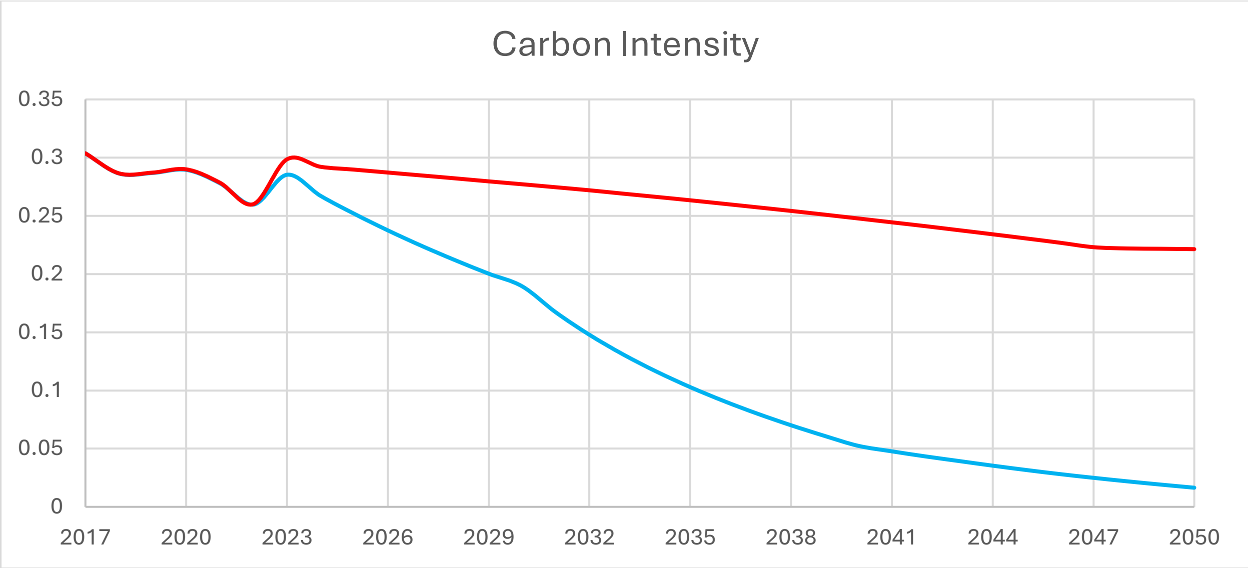

Figure 4.16 – Carbon Intensity for both the scenarios

5. Discussion

This chapter presents a reflection on the results obtained from the model developed for this thesis, in order to interpret their significance, considering the goals of decarbonization and comparing them with those presented in the RNC2050, essential to understand the reliability of them and to see how they differ. The reflection aims to understand the internal logic of the scenarios made and the relevance of the policies behind them. It is also important to define the limitations of both the model and the RNC2050, defining what could be improved and the future research necessary for the advance in the scenario modelling.

5.1 Interpretation of the social variables

As already mentioned, the model delivered two contrasting trajectories, a BaU and an Optimistic scenario, each grounded by different assumptions. Regarding the BaU, the results are aligned with expectations under past trends, indeed it seems that something is changing but not fast enough to reach significant values and moreover, it is missing a complete view of the problems of the society. Human labour decreases due to the demographic decline assumed by INE, since the variable LFRP follows its upwards trend, while the unemployment rate and the hours worked by an engaged individual are assumed to be constant to be more conservative. Therefore, under these assumptions, Portugal has less product from the human labour, even if an engaged individual works the same number of hours. In the Optimistic scenario, human labour decreases even more and at first impact it could be misleading. However, this decline is caused by the four days workweek assumption, reducing the number of hours worked by each individual and balancing more the time spent at work and the free time of each person. In this scenario, the Portugues population is more involved into work, with less people unemployed, therefore the work is more spread across all population. In the RNC2050, the aspect related to the HL is treated differently, since there are 3 types of socio-economic scenarios, regarding 3 different situations: the first one "off-track", in which the current policies are followed, without any structural change in the economy and society, the second one "Pelotão", characterised by the development and application of new technologies which, however, do not alter either the production structures or the lifestyles of the populations, and the third one "Camisola Amarela", dominated by a structural and cross-cutting change in production chains, made possible by the combination of a set of technologies from the 4th Industrial Revolution. The latter resembles the assumptions embedded in the optimistic scenario. The situations described by these 3 socio-economic scenarios are used as instruments for deriving the energetic scenario and the evolution of the emissions, but there is no quantitative link between them. Indeed, the socio-economic variables are just associated to plausible energetic variables that could coexist at the same time, depending on the situation considered. In contrast, this thesis's model uses human labour as direct input into GDP, allowing afterwards endogenous feedback between socio-economic and energy-emission dynamics.

5.2 Investment, Capital and GDP

Regarding the capital in the BaU scenario, it slows down and eventually reverses due to the past trend of investment and depreciation, reflecting the stagnant policy framework. While some investment in renewable still occurs, even leading to a fully renewable electricity supply before 2050, this outcome is misleading since it does not happen because of ambitious policies, but because economic activities slow down, therefore electricity demand declines. In contrast, in the Optimistic scenario capital grows significantly, due to targeted investments across the sectors, taken from RNC2050. The latter hypothesizes big investments in renewables due to an electrification of all the sectors, thus increasing demand of electricity. The transport sector concentrates about 40% of the total investment, reflecting its transformation from oil-based vehicles to electric and hydrogen powered alternatives. For the residential and service sectors most of the investment is associated with the renovation and replacement of electric equipment, improvements in buildings insulation, increasing the thermal comfort and reducing the heating and cooling demand, and the use of heat pumps, which is the most efficient way to provide heating and cooling. The investment in agriculture, forestry and fishing focuses in specific technologies, leading to reductions in fertiliser emissions and increases in sequestration on agricultural land. What is explicitly missing in the RNC2050 project is the evaluation of the depreciation, since there is not an endogenous mechanism for the computation of capital, which represents a limitation of the project.

GDP exhibits varying trajectories depending on the case. In the BaU scenario, it follows a downwards trend due to the mutual decreases in both capital stock and HL. However, the slight increase in TFP prevents a complete collapse of GDP, highlighting the importance and strong influence of technological efficiency in the economy. In fact, in the optimistic scenario, the increase in TFP leads to a significantly higher GDP, even compared to RNC2050. In the latter, GDP is not linked to the energy sector of society, since there is not a connection between TFP and aggregate efficiency, which causes a large difference between this thesis model and the roadmap. The annual growth rates are on average 5.20% for the optimistic scenario and 1.74% for RNC2050, with a difference of €500 billion in total GDP at the end of the study period. This reveals a structural limitation in the RNC2050 model, which is addressed in this thesis by integrating energy dynamics with economic modelling, showing how results can vary significantly if socioeconomic and energetic aspects are linked between each other.

5.3 Assumptions on Costs and Efficiencies

Renewable technology costs and end-use efficiencies are assumed to follow the same trend for both scenarios. This is explained by two main considerations: first, the costs are mostly influenced by technological maturity, raw material prices and the structure of the supply chain, which are drivers operating at a scale well beyond national influence, making reasonable to treat Portugal as a price-taker. For this reason, it is assumed that all technologies decline in cost, except hydropower, based on historical data, aiming at a global progress, as it happened during the past years; second, assuming identical end-use efficiencies for both the scenarios allows a clearer identification of the differences in other variables, such as emissions and GDP, giving more importance to changes in the structure and behaviour, rather than in technologies. Moreover, the rate at which the efficiencies grow is relatively modest in both real-world data and projections. Therefore, this enables the model to isolate the impact of electrification, changes in the sectors and exergy redistribution without mixing these effects with assumptions about technologies.

5.4 Future Renewable Deployment

Another relevant difference between the scenarios is the evolution of the total renewable power installed. In the Optimistic scenario, at the end of the study period, it is two times bigger than the BaU scenario. This is mainly due to the scale of electrification envisioned in this scenario, thus big volumes of electricity are needed and renewable technologies are in line both with this demand and with the goal of carbon neutrality. In order to satisfy this demand, new technologies are also needed, such as hydrogen, which alone accounts for over one-quarter of the total renewable capacity in 2050. The BaU scenario, despite conservative assumptions, still shows some growth in renewable capacity, reflecting the cost-competitiveness and the importance behind them. In this scenario, the coverage of electricity demand by renewables occurs mainly because the demand slightly decreases, which is a symptom of economic slowdown rather than a success in energy transition.

5.5 Comparison of Total Final Exergy

Figure 5.1 illustrates the evolution of the total final exergy across all the cases. In the BaU and Optimistic Scenario, this data is derived from the internal linkage between economy and energy system, first computing the total useful exergy and then dividing by the aggregate efficiency. In contrast, in the RNC2050 this variable is just determined through the assumptions made, without incorporating an endogenous process. As for GDP, a clear divergence emerges between the model developed in this thesis and the RNC2050 roadmap. In the latter, a big electrification occurs, and as consequence the final exergy needed decreases, due to the higher efficiency of electricity compared to the other carriers. In the Optimistic scenario, the total final exergy is obtained endogenously, and the rising behaviour is driven by GDP growth, which itself results primarily from increasing TFP. As for the roadmap, electrification also occurs, but in this case the result is different: the increase of the aggregate efficiency leads to a higher total useful exergy, so also a higher total final exergy but better produced, considering the rising of the efficiencies and the process of electrification. Under these assumptions, the demand of final exergy increases, but in both cases the electricity demand is covered by renewables by 2050. Thus, since the renewable power installed is the same, it could be that there is an overestimation of the electricity produced by renewable energies in the Optimistic scenario or an underestimation in the RNC2050, not considering the case in which the electricity produced in the roadmap coincides with the Optimistic scenario and as result part of it is not used.

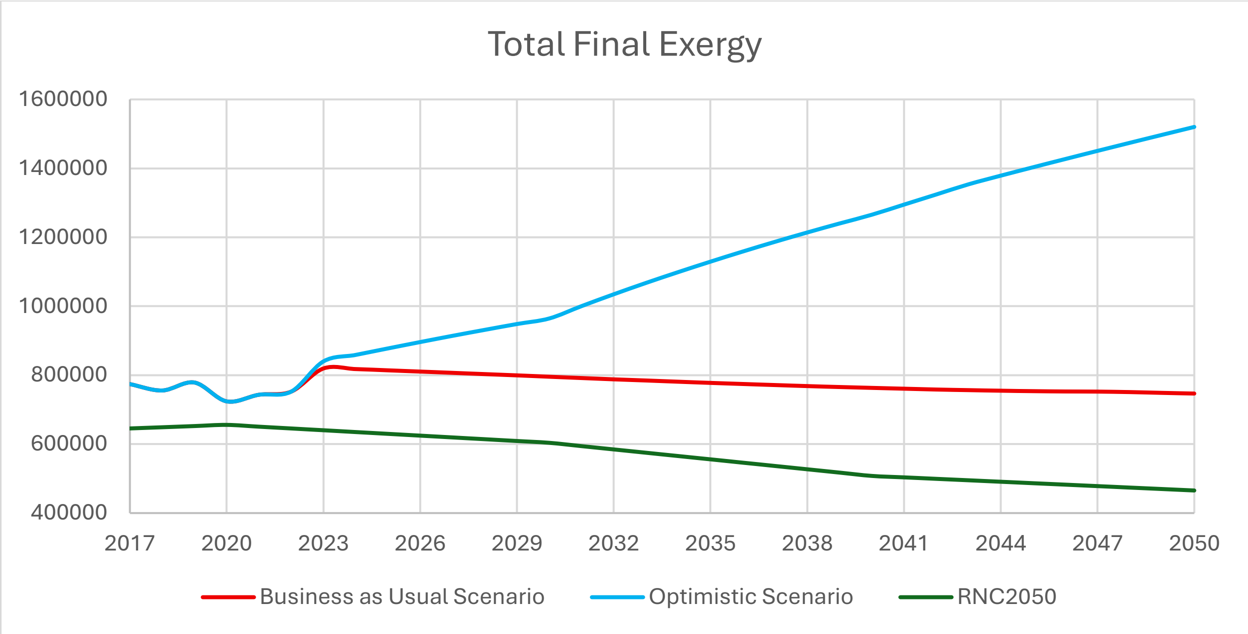

Figure 5.1 – Evolution of the Total Final Exergy for the three cases

5.6 Emissions Trajectories and Carbon Neutrality

One of the most policy-relevant results concerns CO_2 emissions. For both scenarios there is a declining trend, therefore they decrease in any case, however they differ in scale and reason. In the BaU, emissions fall gradually mainly due to reduced economic activity and lower final exergy demand. The total amount of emissions at the end of the period is around 40 Mt CO_2 per year, which is far above the thresholds compatible with national and international climate targets, indeed, by 2050, it is expected to reach carbon neutrality. In the Optimistic scenario, emissions decrease more sharply, reaching a final amount of almost 14 Mt CO_2 per year, which mostly represents the emissions generated by processes difficult to electrify. Thus, it is important to take into account carbon capture, since thanks to it, carbon neutrality is reachable in most of the cases. Under RNC2050 assumptions, 13 Mt CO_2 correspond to the quantity that could be offset though forest and land-based carbon sinks, considering an improvement of the management and of the practices, such as fires prevention and afforestation. Despite the differences in structure and methodologies, the final total emissions estimated by this thesis' model converge well with those of the roadmap, giving more credibility to both results. Indeed, according to the results, Portugal could achieve carbon neutrality by 2050 and although these emissions represent just a global small fraction, this is a valuable demonstration of the feasibility of the challenge.

While the BaU scenario extrapolates past trends, Portugal, in reality, is decoupling from this track. Since the publication of the roadmap, the government has not only maintained but also intensified its commitment and announced that current conditions may allow Portugal to become carbon neutral by 2045, five years ahead of schedule. The congruence of the Optimistic scenario with the RNC2050 shows that net zero emissions is an achievable target, but it requires strong sustainable policies, technologies development and social commitment.

6. Conclusion

6.1 Overview of Key Results

This thesis sought to study the macroeconomic impacts of Portugal's energy transition through an original modelling strategy that takes into account a bridge between energetic and socioeconomic factors, using an exergy analysis as a basis for the evaluation of overall needs. This study designed two opposing long-term scenarios: a Business-as-Usual projection based on historical trends and an ambitious looking-forward case, Optimistic scenario, in agreement with the RNC2050 roadmap assumptions.

The results show two very different directions for the Portuguese energy system and economy. The BaU scenario describes a country that continues on traditional paths, experiencing population decline, steady increases in labour participation and low capital accumulation. While it still observes some CO_2 emission reduction, this is primarily due to economic stagnation and low energy demand and not structural decarbonization. Instead, the Optimistic scenario describes a change of the system. Despite a reduction in total working hours from a 4-day week, human labour is more evenly distributed. Capital stock rises as investments are higher than the depreciations. Overall, the country reaches carbon neutrality, considering the carbon capture assumed in the roadmap, with massive electrification, transforming the energy mix, and dramatic increase in exergy efficiency.

These are not only quantitative differences but reflect different conceptions of the future. BaU represents a society resistant to changes, while Optimistic embodies options to route Portugal to decarbonization. The fact that CO_2 emissions for the Optimistic scenario are almost as low as in the RNC2050 confirms the internal consistency and external plausibility of the model.

6.2. On the Adequacy of the 2050 Carbon Neutrality Target

With the right effort, this thesis' model and the roadmap show that carbon neutrality is achievable by 2050, however one question in need of answer is whether this result is sufficient considering the present state of scientific understanding. (IPCC, 2022) declared that to limit global warming to 1.5 ° C, the world must reduce greenhouse gas emissions by at least 43% by 2030 compared to 2010 levels and net-zero CO_2 emissions by around 2050 worldwide and it is important to understand that these are not arbitrary deadlines, but physical facts. The optimistic scenario illustrates how Portugal could reduce its net CO_2 emissions to zero in 2050 as per the long-term goal of the IPCC. However, the model also illustrates that the emission reduction in the initial period is not sufficient to meet the target of 2030. Indeed, emissions don't begin falling significantly until after 2030, after the lag corresponding to the period required for social change and capital accumulation. This lag has important implications. As the IPCC itself states: "Every year matters, every choice matters, every fraction of a degree matters." Putting off the emissions cut by 2030 will risk overshooting the 1.5°C threshold and trigger feedback loops and irremediable harms such as destabilization of ice sheets, loss of ecosystems or enhancement of extreme weather. From a policy viewpoint, this is the argument that 2050 would not be an endpoint but a frontier to be reached as soon as can be arranged and Portugal has already spoken about making the 2045 target possible, being more ambitious than many other European states. That is a positive trend and in the spirit of acting in advance, but even that may prove too little. Deep decarbonization requires not just planning in 2045 or 2050, but also strong policy frameworks and investments over the next years. The trajectory of the emissions is just as important as the goal and getting both goals into alignment with what IPCC stated is the only way to ensure environmental protection and prevention. Therefore, while this thesis' findings confirm that Portugal can reach the IPCC net-zero objective of 2050, the current path still falls short of 2030 achievement.

6.3. Gaps and Limitations in the Model

While the model developed in this thesis provides a valuable contribution to long-term energy-economy modelling, there are several important limitations that need to be acknowledged.

A first major limitation lies in the treatment of carbon capture technologies. As opposed to the RNC2050 roadmap, which assumes that residual emissions in 2050 will be compensated by forest and other land uses, this model does not include any active or passive carbon capture mechanism, but it just assumes the same value of the RNC2050 for the emissions absorbed, without a quantitative analysis and without risk, trade-off and technological uncertainty modelling of CCUS. This omission, though deliberate, delimits the scope of the analysis: in the absence of negative emissions, the trajectory of the model towards carbon neutrality depends solely on upstream reduction of final exergy demand and electrification, which might not be feasible in every sector.

Side by side with this is the absence of circular economy mechanisms within the structure of the model. Practices such as recycling, reuse of products, material efficiency and product lifetime extension can, in fact, significantly reduce the need for primary resource extraction and, in turn, the associated energy and emissions. But, as circularity is difficult to quantify in terms of exergy demand and is very context-dependent, it is not included in the present modelling approach. This omission limits the system boundary and does not enable the analysis to take into consideration potential reductions on the demand side. The RNC2050 refers the circular economy as a guiding principle, and it considers the inclusion of these processes as part of the narrative of the socioeconomic scenarios developed.

Another omission is the absence of air quality considerations, which instead are faced in the roadmap, since many of the processes involved are responsible for environmental problems, such as degradation of air quality, acidification and eutrophication, causing damage to ecosystems with the consequent loss of biodiversity and human health problems, particularly respiratory and cardiovascular problems. Although the transition away from fossil fuels, especially in the transportation and residential sectors, would reap significant benefits in terms of reduced air pollutants, these effects are not inventoried. Including air quality would mean connecting energy system outputs to atmospheric models and pollutant inventories, which lies beyond the scope of the present task but is a logical way forward for future work.

Addressing these limitations in future work would require additional modelling layers or hybrid approaches that incorporate material flows, sector-specific employment data, and environmental indicators.

6.4. Missing Components in RNC2050 and Comparative Value of This Thesis

As already noticed, the RNC2050 roadmap also presents certain structural limitations. While its role as a guide document cannot be questioned, a comparative evaluation with this thesis' model reveals gaps to be bridged in future editions. The most visible is the lack of a direct connection between the energy system and the socioeconomic aspects. In the RNC2050, the energy dynamics are managed by pre-specification sectoral dynamics and technological assumptions, based on three qualitative socioeconomic scenarios, however these are not embedded in a mathematical economic model. Therefore, labour input, productivity, capital accumulation or investment variables are not dynamically linked to energy use or technological improvement. This isolation could lead to scenarios in which apparently these two areas are connected, but in reality, they represent different cases, not being interconnected endogenously between them.

Second, the roadmap does not address energy in exergy terms, thus neglecting to construct a more complete representation of how energy actually is used and transformed in the economy. This, in turn, enables the computation of Total Factor Productivity, allowing the endogenous connection between the energy and the socioeconomic sector. The absence of this framework in RNC2050 precludes the roadmap from fully analysing the potential impact of variation in energy efficiency or electrification trends on economic performance over the long run.

A third significant limitation concerns handling of carbon capture and storage. The RNC2050 theory assumes that approximately 13 $MtCO_2$ residual emissions will remain in 2050 and will be fully offset by terrestrial sinks, primarily through improved forest and land management. While this approach aligns with national wildland fire prevention and afforestation policies, it is the only declared mitigation mechanism beyond energy decarbonization. Other CCS or CCUS forms, such as industrial point-source capture, direct air capture or bioenergy with CCS are excluded. Since the natural uncertainty regarding land sink long-term sequestration potential and international increasing interest in engineered solutions, this could represent a significant omission.

6.5. Contribution to European Modelling Frameworks: Relevance to the MAPS Project

The modelling activity presented in this thesis also contributes to the broader European research environment of transition towards sustainability, particularly to the MAPS project (Models, Assessment, and Policies for Sustainability). The MAPS project is funded through the Horizon Europe programme whose objective is to develop new modelling schemes transcending conventional economic thought by accounting for biophysical and environmental constraints, social justice and post-growth perspectives, since the pursuit of economic growth is failing to improve people's lives in European nations. This thesis aids those objectives through proposing a model that links the dynamics of energy systems to macroeconomics through a new definition of productivity using exergy-based total factor productivity. By the incorporation of energy efficiency, renewable deployment, and labour dynamics into macroeconomic outcomes, this model shares the MAPS agenda of establishing simulation tools that are sensitive both to environmental limits and to human well-being. The forward-looking projections of scenarios built in this thesis, particularly the optimistic scenario, give a bottom-up assessment of how a transition would be possible under high-difficulty decarbonisation pathways, all grounded on empirical data and national aspirations. Furthermore, the thesis fulfils some of the identical research objectives of MAPS, like the reconsideration of GDP as the unifying policy measure, strategies supported by people, such as reducing working hours, and sectoral structural change over time simulated. While changes in behaviour or nonlinear feedback are not yet included in the model, its structure provides it as a simple candidate to be merged with IAMs of higher complexity in the future. In this way, it can be employed as an effective module in the development of the future generation participatory modelling tools enabled by MAPS. Lastly, this thesis advances the shared European goal of designing alternative economic paths that are socially equitable and environmentally sustainable. By embedding national decarbonisation roadmap within an open and responsive modelling platform, it offers analysis that can subsequently feedback into informing academic knowledge as well as actual policy decisions in the coming years.

6.6. Recommendations for Future Work

While the model described here creates a new connection between macroeconomic variables and energy system evolution, there are a few directions of future research where it can be made more realistic, robust and policy oriented. Firstly, despite the fact that the model identifies long-term relationships between exergy, capital accumulation and productivity, it is perhaps possible to improve it by embedding of circular economy processes. As currently designed, the model is not incorporated with material efficiency, prolongation of product life or waste minimization policy. Incorporating such mechanisms would offer a more accurate representation of the material and energy connection and allow to quantify by how much circularity can minimize the exergy demand of the economic system.

Similarly, impacts of air pollutants and co-pollutants, such as NO_x, SO_x and $PM_{2.5}$ are not covered. Their inclusion would not only provide a fuller environment analysis, but also allow policymakers to make evaluations of the benefits and trade-offs of decarbonisation policies, most particularly in urban areas where health benefits are significant.

The treatment of carbon dioxide represents another limitation. In RNC2050, forestry and land use are assumed to offset the remaining emissions passively, but no active quantification or modelling of these processes is done. Other carbon capture and utilization strategies, such as bioenergy with Carbon Capture and Storage, industrial carbon capture or other technologies like Direct Air Capture, are completely absent. A further exploration of such routes would provide a clearer sense of how carbon neutrality could be achieved operationally and at what cost.

Moreover, it is highly recommended to perform more systematic sensitivity analysis. This would involve systematically varying key assumptions, such as fossil fuel prices, exergy efficiency levels or rates of investment, and examining sensitivity in the model's outputs. Sensitivity testing not only would add credibility to the results but also would tell us which parameters most strongly influence the trajectory of the model and hence would identify leverage points for policy.

Another area of future work is the improvement of the socioeconomic dimension. The model now operates with macroeconomic aggregates, but including groups disaggregation, such as age groups or region groups, could yield crucial insights on the distributional effects of energy transitions. This would be of direct relevance in informing just transition policies and preventing decarbonisation to enhance social inequalities.

Lastly, the explicit modelling of behaviour change and sufficiency deserves more attention, since energy demand is mainly reacting to technological and economic factors. When including changes on the demand side, such as lower mobility, altered diets or altered consumption patterns, in future models, other decarbonisation paths less dependent on growth on the supply side and more on adjusting lifestyles might be uncovered.

Bibliography

Alvarenga, A., Marta-Pedroso, C., Santos, J., Felício, L., & Almeida Serra, L. (2017). *MEET2030 TOWARDS A CARBON NEUTRAL ECONOMY HOW IS PORTUGAL GOING TO CREATE EMPLOYMENT AND GROW? Prepared by: MEET 2030 Team*.

Banco de Portugal. (2018). *Projeções económicas para Portugal atualizadas em: 28 de março de 2018*.

Capros, P., Paroussos, L., Fragkos, P., Tsani, S., Boitier, B., Wagner, F., Busch, S., Resch, G., Blesl, M., & Bollen, J. (2014). Description of models and scenarios used to assess European decarbonisation pathways. *Energy Strategy Reviews*, *2*(3–4), 220–230. https://doi.org/10.1016/j.esr.2013.12.008

Fidalgo Pinto Veloso da Silva, A., Filipe Fernandes Prada, R., Alexandra dos Santos Costa Sousa, T., & António Chaves Saraiva de Melo Supervisor, F. (2020). *exergyX: A Game on Management of Energy Systems Information Systems and Computer Engineering Examination Committee*.

INE. (2017). *Projeções de População Residente - 2018-2080*.

INE. (2020). *Projeções de População Residente – 2018-2080*.

IPCC. (2022). *IPCC AR6 PressRelease*.

IRENA. (2020). *Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5⁰C Climate Goal*. International Renewable Energy Agency. www.irena.org/publications

IRENA. (2024). *Renewable power generation costs in 2023*. www.irena.org

IRENA. (2025). *Renewable capacity statistics 2025*. International Renewable Energy Agency. www.irena.org

Santos, J., Borges, A. S., & Domingos, T. (2021). Exploring the links between total factor productivity and energy efficiency: Portugal, 1960–2014. *Energy Economics*, *101*. https://doi.org/10.1016/j.eneco.2021.105407

Serrenho, A. C., Sousa, T., Warr, B., Ayres, R. U., & Domingos, T. (2014). Decomposition of useful work intensity: The EU (European Union)-15 countries from 1960 to 2009. *Energy*, *76*, 704–715. https://doi.org/10.1016/j.energy.2014.08.068

Serrenho, A. C., Warr, B., Sousa, T., Ayres, R. U., & Domingos, T. (2016). Structure and dynamics of useful work along the agriculture-industry-services transition: Portugal from 1856 to 2009. *Structural Change and Economic Dynamics*, *36*, 1–21. https://doi.org/10.1016/j.strueco.2015.10.004

United Nations. (2024). *The Sustainable Development Goals Report*.

Appendices

Business as Usual	Hours worked by an engaged individual	Unemployement rate	Working age Population	Labour Force Partecipation rate	Human Labour
1992	1876.256043	0.041	6663818	0.687	8237407970
1993	1863.66193	0.055	6692136	0.681	8026215432
1994	1859.329583	0.068	6730554	0.676	7884420900
1995	1897.717808	0.071	6766666	0.674	8040480148
1996	1898.771301	0.072	6801726	0.675	8089907219
1997	1893.720519	0.067	6837989	0.682	8239679158
1998	1909.186662	0.049	6873721	0.706	8811006266
1999	1910.954261	0.044	6914880	0.709	8956515207
2000	1920.561459	0.039	6963754	0.711	9138283324
2001	1903.931705	0.04	6992760	0.718	9176892962
2002	1896.985396	0.05	7012599	0.726	9174939705
2003	1889.955472	0.063	7018275	0.728	9048006914
2004	1896.087619	0.066	7015481	0.726	9019850766
2005	1898.144004	0.076	7018372	0.732	9010493827
2006	1886.338686	0.076	7027921	0.736	9015635148
2007	1903.484288	0.08	7039144	0.739	9109644133
2008	1890.361861	0.076	7033726	0.739	9079183682
2009	1890.79404	0.094	7025090	0.734	8833247004
2010	1893.635619	0.108	7001126	0.737	8715587152
2011	1870.603321	0.135	6952259	0.728	8189457449
2012	1853.090179	0.165	6894640	0.725	7734506897
2013	1863.216461	0.172	6825389	0.724	7623591615
2014	1870.834192	0.145	6771316	0.73	7906738128
2015	1878.60165	0.129	6736280	0.735	8101404636
2016	1884.829651	0.115	6691202	0.739	8248290634
2017	1873.619081	0.092	6657888	0.75	8495029625
2018	1867.852012	0.072	6624826	0.757	8692822192
2019	1864.58836	0.066	6587247.23	0.76	8718613004
2020	1864.58836	0.07	6549668.46	0.749	8506816251
2021	1864.58836	0.067	6512089.69	0.76	8609909339
2022	1864.58836	0.061	6474510.92	0.774	8773976961
2023	1864.58836	0.065	6436932.15	0.788	8843002114
2024	1864.58836	0.064	6399353.38	0.792	8845453272
2025	1864.58836	0.064	6361774.62	0.794230769	8818278375
2026	1864.58836	0.064	6324195.85	0.796461538	8790810870
2027	1864.58836	0.064	6286617.08	0.798692308	8763050757
2028	1864.58836	0.064	6249038.31	0.800923077	8734998037
2029	1864.58836	0.064	6211459.54	0.803153846	8706652708
2030	1864.58836	0.064	6173880.77	0.805384615	8678014772

2031	1864.58836	0.064	6136302	0.807615385	8649084227
2032	1864.58836	0.064	6098723.23	0.809846154	8619861075
2033	1864.58836	0.064	6061144.46	0.812076923	8590345315
2034	1864.58836	0.064	6023565.69	0.814307692	8560536947
2035	1864.58836	0.064	5985986.92	0.816538462	8530435971
2036	1864.58836	0.064	5948408.15	0.818769231	8500042387
2037	1864.58836	0.064	5910829.38	0.821	8469356196
2038	1864.58836	0.064	5873250.62	0.823230769	8438377396
2039	1864.58836	0.064	5835671.85	0.825461538	8407105989
2040	1864.58836	0.064	5798093.08	0.827692308	8375541974
2041	1864.58836	0.064	5760514.31	0.829923077	8343685351
2042	1864.58836	0.064	5722935.54	0.832153846	8311536120
2043	1864.58836	0.064	5685356.77	0.834384615	8279094281
2044	1864.58836	0.064	5647778	0.836615385	8246359834
2045	1864.58836	0.064	5610199.23	0.838846154	8213332780
2046	1864.58836	0.064	5572620.46	0.841076923	8180013117
2047	1864.58836	0.064	5535041.69	0.843307692	8146400847
2048	1864.58836	0.064	5497462.92	0.845538462	8112495969
2049	1864.58836	0.064	5459884.15	0.847769231	8078298483
2050	1864.58836	0.064	5422305.38	0.85	8043808389

Table A.1 – Social variables, BaU scenario

Business as Usual	Hours worked by an engaged individual	Unemployement rate	Working age Population	Labour Force Partecipation rate	Human Labour
1992	1876.256043	0.041	6663818	0.687	8237407970
1993	1863.66193	0.055	6692136	0.681	8026215432
1994	1859.329583	0.068	6730554	0.676	7884420900
1995	1897.717808	0.071	6766666	0.674	8040480148
1996	1898.771301	0.072	6801726	0.675	8089907219
1997	1893.720519	0.067	6837989	0.682	8239679158
1998	1909.186662	0.049	6873721	0.706	8811006266
1999	1910.954261	0.044	6914880	0.709	8956515207
2000	1920.561459	0.039	6963754	0.711	9138283324
2001	1903.931705	0.04	6992760	0.718	9176892962
2002	1896.985396	0.05	7012599	0.726	9174939705
2003	1889.955472	0.063	7018275	0.728	9048006914
2004	1896.087619	0.066	7015481	0.726	9019850766
2005	1898.144004	0.076	7018372	0.732	9010493827
2006	1886.338686	0.076	7027921	0.736	9015635148
2007	1903.484288	0.08	7039144	0.739	9109644133
2008	1890.361861	0.076	7033726	0.739	9079183682
2009	1890.79404	0.094	7025090	0.734	8833247004
2010	1893.635619	0.108	7001126	0.737	8715587152

2011	1870.603321	0.135	6952259	0.728	8189457449
2012	1853.090179	0.165	6894640	0.725	7734506897
2013	1863.216461	0.172	6825389	0.724	7623591615
2014	1870.834192	0.145	6771316	0.73	7906738128
2015	1878.60165	0.129	6736280	0.735	8101404636
2016	1884.829651	0.115	6691202	0.739	8248290634
2017	1873.619081	0.092	6657888	0.75	8495029625
2018	1867.852012	0.072	6624826	0.757	8692822192
2019	1864.58836	0.066	6607282.51	0.76	8745130883
2020	1851.214542	0.07	6589739.02	0.749	8497471846
2021	1837.840724	0.067	6572195.52	0.76	8564728136
2022	1824.466906	0.061	6554652.03	0.774	8691448961
2023	1811.093088	0.065	6537108.54	0.788	8722968362
2024	1797.71927	0.064	6519565.05	0.792	8688434406
2025	1784.345452	0.06346154	6502021.55	0.796153846	8650674243
2026	1770.971634	0.06292308	6484478.06	0.800307692	8612294345
2027	1757.597816	0.06238462	6466934.57	0.804461538	8573299211
2028	1744.223998	0.06184615	6449391.08	0.808615385	8533693355
2029	1730.85018	0.06130769	6431847.58	0.812769231	8493481299
2030	1717.476362	0.06076923	6414304.09	0.816923077	8452667581
2031	1704.102544	0.06023077	6396760.6	0.821076923	8411256751
2032	1690.728725	0.05969231	6379217.11	0.825230769	8369253370
2033	1677.354907	0.05915385	6361673.62	0.829384615	8326662013
2034	1663.981089	0.05861538	6344130.12	0.833538462	8283487268
2035	1650.607271	0.05807692	6326586.63	0.837692308	8239733735
2036	1637.233453	0.05753846	6309043.14	0.841846154	8195406025
2037	1623.859635	0.057	6291499.65	0.846	8150508765
2038	1610.485817	0.05646154	6273956.15	0.850153846	8105046592
2039	1597.111999	0.05592308	6256412.66	0.854307692	8059024156
2040	1583.738181	0.05538462	6238869.17	0.858461538	8012446119
2041	1570.364363	0.05484615	6221325.68	0.862615385	7965317159
2042	1556.990545	0.05430769	6203782.18	0.866769231	7917641962
2043	1543.616727	0.05376923	6186238.69	0.870923077	7869425230
2044	1530.242908	0.05323077	6168695.2	0.875076923	7820671675
2045	1516.86909	0.05269231	6151151.71	0.879230769	7771386023
2046	1503.495272	0.05215385	6133608.22	0.883384615	7721573014
2047	1490.121454	0.05161538	6116064.72	0.887538462	7671237398
2048	1476.747636	0.05107692	6098521.23	0.891692308	7620383938
2049	1463.373818	0.05053846	6080977.74	0.895846154	7569017412
2050	1450	0.05	6063434.25	0.9	7517142607

Table A.2 – Social variables, Optimistic Scenario

CAPITAL	Industry	Transport	Residencial	Services	Agriculture/Forestry/Fishing	Total

2000	52.0873	21.7184	255.3092	139.2453	9.5557	477.9159
2001	55.1883	22.8597	261.968	146.8615	9.6967	496.5742
2002	57.8863	23.7974	267.8576	153.3925	9.861	512.7948
2003	60.3418	24.5576	271.1163	158.5295	9.9402	524.4854
2004	62.5719	25.136	273.8721	163.6816	10.1153	535.3769
2005	65.0816	25.5939	276.5022	167.959	10.2091	545.3458
2006	67.7764	26.1692	278.195	171.7153	10.256	554.1119
2007	71.0234	27.1342	279.214	175.349	10.3362	563.0568
2008	74.0098	28.2218	278.706	179.7174	10.3823	571.0373
2009	76.0907	29.2338	276.8148	182.7495	10.3544	575.2432
2010	77.9743	28.9094	274.0818	187.2105	10.3061	578.4821
2011	79.1615	29.3618	270.567	186.9031	10.227	576.2204
2012	79.2803	28.7659	265.9902	183.6248	10.0775	567.7387
2013	79.1511	28.1515	260.772	180.3327	9.9626	558.3699
2014	79.211	27.47	255.6263	177.6168	9.9045	549.8286
2015	79.0765	27.4193	250.658	176.1321	9.9987	543.2846
2016	79.3905	27.0545	246.1172	174.9201	10.0337	537.516
2017	80.6131	27.0182	242.0709	175.0649	10.1714	534.9385
2018	82.1518	26.9132	238.445	175.9142	10.3007	533.7249
2019	83.4335	26.9947	234.9847	177.7918	10.447	533.6517
2020	84.2382	26.9721	231.1778	178.7445	10.6361	531.7687
2021	86.0842	26.9326	228.2773	180.2278	10.8838	532.4057
2022	88.1075	27.301	225.5689	181.6661	11.0464	533.6899

Table B.3 – Historical Capital

INVESTMENT	Industry	Transport	Residencial	Services	Agriculture/Fishing/Forestry	Total
2000	6.9325	2.7492	14.2547	19.891	0.9877	44.8151
2001	6.2634	3.3949	13.893	21.7246	1.0154	46.2913
2002	5.7404	3.5055	13.4254	21.9757	1.116	45.763
2003	5.6099	4.0053	11.2741	21.1423	1.0518	43.0834
2004	5.7542	3.7923	10.9544	20.8569	1.1507	42.5085
2005	6.4587	3.7694	10.9591	20.4614	0.9791	42.6277
2006	6.891	3.4987	10.2358	20.457	0.9492	42.0317
2007	7.7258	2.9607	9.7232	20.8128	0.9682	42.1907
2008	8.6468	3.2108	8.4301	21.3976	1.0022	42.6875
2009	8.1351	3.2525	7.2245	20.4974	0.8589	39.9684
2010	8.1626	1.3557	6.4653	20.8757	0.9117	37.771
2011	7.6118	2.2942	5.7366	17.4731	0.8905	34.0062
2012	6.6288	1.4696	5.2986	13.6669	0.8781	27.942
2013	6.3806	1.4714	4.567	13.3912	0.9114	26.7216
2014	6.5698	1.3691	4.529	13.7331	0.9578	27.1588
2015	6.4294	1.8681	4.5971	15.3039	1.1116	29.3101
2016	6.9622	1.6287	4.9197	15.3923	1.055	29.9579

2017	8.0532	1.9438	5.3217	16.9093	1.1382	33.3662
2018	8.5546	1.8375	5.663	17.9789	1.1194	35.1534
2019	8.5605	2.0515	5.7613	19.5213	1.129	37.0236
2020	8.3117	1.9884	5.3511	19.3649	1.1885	36.2046
2021	9.503	2.1811	6.1815	19.9656	1.2523	39.0835
2022	10.0172	2.6349	6.3237	20.5271	1.1821	40.685

Table B.4 – Historical Investments

DEPRECIATION	**Industry**	**Transport**	**Residencial**	**Services**	**Agriculture/Fishing/Forestry**	**Total**
2001	3.1624	2.2536	7.2342	14.1084	0.8744	27.633
2002	3.0424	2.5678	7.5358	15.4447	0.9517	29.5424
2003	3.1544	3.2451	8.0154	16.0053	0.9726	31.3928
2004	3.5241	3.2139	8.1986	15.7048	0.9756	31.617
2005	3.949	3.3115	8.329	16.184	0.8853	32.6588
2006	4.1962	2.9234	8.543	16.7007	0.9023	33.2656
2007	4.4788	1.9957	8.7042	17.1791	0.888	33.2458
2008	5.6604	2.1232	8.9381	17.0292	0.9561	34.707
2009	6.0542	2.2405	9.1157	17.4653	0.8868	35.7625
2010	6.279	1.6801	9.1983	16.4147	0.96	34.5321
2011	6.4246	1.8418	9.2514	17.7805	0.9696	36.2679
2012	6.51	2.0655	9.8754	16.9452	1.0276	36.4237
2013	6.5098	2.0858	9.7852	16.6833	1.0263	36.0904
2014	6.5099	2.0506	9.6747	16.449	1.0159	35.7001
2015	6.5639	1.9188	9.5654	16.7886	1.0174	35.8541
2016	6.6482	1.9935	9.4605	16.6043	1.02	35.7265
2017	6.8306	1.9801	9.368	16.7645	1.0005	35.9437
2018	7.0159	1.9425	9.2889	17.1296	0.9901	36.367
2019	7.2788	1.97	9.2216	17.6437	0.9827	37.0968
2020	7.507	2.011	9.158	18.4122	0.9994	38.0876
2021	7.657	2.2206	9.082	18.4823	1.0046	38.4465
2022	7.9939	2.2665	9.0321	19.0888	1.0195	39.4008

Table B.5 – Historical Depreciations

	Mean Investment/GDP	Mean Depreciation/Capital
Industry	0.182512988	0.08540539
Transport	0.140684458	0.074788916
Residencial	0.201851534	0.038676179
Services	0.160891038	0.097332474
Agriculture/Fishing/Forestry	0.120203495	0.098006549

Table B.6 – Historical means from 2012 to 2022

INVESTMENT	Industry	Transport	Residential	Services	Agriculture/Forestry/Fishing	Total
2023	3.045424	14.94634	0.676761	12.39048	1.140721	32.19973
2024	3.105138	15.2394	0.690031	12.63343	1.143016	32.81102
2025	3.166023	15.53821	0.703561	12.88115	1.145319	33.43427
2026	3.228102	15.84288	0.717356	13.13372	1.14763	34.06969
2027	3.291398	16.15353	0.731422	13.39124	1.149949	34.71754
2028	3.355936	16.47027	0.745763	13.65382	1.152276	35.37806
2029	3.421738	16.79321	0.760386	13.92154	1.154611	36.05149
2030	3.488831	17.12249	0.775296	14.19451	1.156954	36.73808
2031	6.130562	10.09146	1.185747	16.9915	1.159305	35.55857
2032	6.250769	10.28933	1.208996	17.32466	1.164778	36.23854
2033	6.373333	10.49108	1.232702	17.66436	1.167083	36.92856
2034	6.4983	10.69679	1.256873	18.01072	1.169398	37.63208
2035	6.625718	10.90653	1.281517	18.36387	1.171721	38.34936
2036	6.755634	11.12039	1.306645	18.72395	1.174053	39.08067
2037	6.888097	11.33843	1.332266	19.09108	1.176394	39.82627
2038	7.023158	11.56075	1.358389	19.46542	1.178744	40.58646
2039	7.160867	11.78744	1.385024	19.84709	1.181102	41.36152
2040	7.301276	12.01856	1.412181	20.23625	1.183469	42.15174
2041	6.847045	17.38567	2.374255	21.3683	1.185845	49.16112
2042	6.981301	17.72657	2.420809	21.78728	1.188229	50.10419
2043	7.118189	18.07415	2.468276	22.21448	1.190621	51.06572
2044	7.257762	18.42854	2.516674	22.65006	1.193022	52.04606
2045	7.400071	18.78989	2.56602	23.09418	1.195432	53.04559
2046	7.54517	19.15832	2.616334	23.54701	1.197849	54.06468
2047	7.693115	19.53397	2.667635	24.00871	1.200275	55.10371
2048	7.84396	19.91699	2.719941	24.47947	1.20271	56.16307
2049	7.997763	20.30752	2.773274	24.95946	1.205152	57.24317
2050	8.154582	20.70571	2.827652	25.44886	1.207603	58.34441

Table B.7 – RNC2050 Investments De-actualized, constant price 2015

BaU Scenario, [GW]	Hydroelectric	Onshore Wind Power	Offshore Wind Power	Solar PV	Batteries	Total
2015	6.168	4.937	0	0.452	0	11.557
2016	6.96	5.124	0	0.533	0	12.617
2017	7.226	5.124	0	0.619	0	12.969
2018	7.236	5.172	0	0.717	0	13.125
2019	7.262	5.223	0	0.97	0	13.455

2020	7.241	5.122	0.025	1.191	0.01	13.589
2021	7.255	5.427	0.025	1.817	0.01	14.534
2022	8.189	5.538	0.025	2.817	0.025	16.594
2023	8.187	5.538	0.025	4.04	0.025	17.815
2024	8.347	5.583	0.025	5.808	0.03	19.793
2025	8.347	5.6507	0.025	6.353846	0.03	20.40655
2026	8.347	5.7214	0.025	6.899692	0.03	21.02309
2027	8.347	5.7951	0.025	7.445538	0.03	21.64264
2028	8.347	5.8718	0.025	7.991385	0.03	22.26518
2029	8.347	5.9515	0.025	8.537231	0.03	22.89073
2030	8.347	6.0342	0.025	9.083077	0.03	23.51928
2031	8.347	6.1199	0.025	9.628923	0.03	24.15082
2032	8.347	6.2086	0.025	10.17477	0.03	24.78537
2033	8.347	6.3003	0.025	10.72062	0.03	25.42292
2034	8.347	6.395	0.025	11.26646	0.03	26.06346
2035	8.347	6.4927	0.025	11.81231	0.03	26.70701
2036	8.347	6.5934	0.025	12.35815	0.03	27.35355
2037	8.347	6.6971	0.025	12.904	0.03	28.0031
2038	8.347	6.8038	0.025	13.44985	0.03	28.65565
2039	8.347	6.9135	0.025	13.99569	0.03	29.31119
2040	8.347	7.0262	0.025	14.54154	0.03	29.96974
2041	8.347	7.1419	0.025	15.08738	0.03	30.63128
2042	8.347	7.2606	0.025	15.63323	0.03	31.29583
2043	8.347	7.3823	0.025	16.17908	0.03	31.96338
2044	8.347	7.507	0.025	16.72492	0.03	32.63392
2045	8.347	7.6347	0.025	17.27077	0.03	33.30747
2046	8.347	7.7654	0.025	17.81662	0.03	33.98402
2047	8.347	7.8991	0.025	18.36246	0.03	34.66356
2048	8.347	8.0358	0.025	18.90831	0.03	35.34611
2049	8.347	8.1755	0.025	19.45415	0.03	36.03165
2050	8.347	8.3182	0.025	20	0.03	36.7202

Table C.8 – GW of Renewable Power Installed, BaU Scenario

Optimistic Scenario, [GW]	Hydroelectric	Onshore Wind Power	Offshore Wind Power	Solar PV	Batteries	Hydrogen	Total
2015	6.168	4.937	0	0.452	0	0	11.557
2016	6.96	5.124	0	0.533	0	0	12.617
2017	7.226	5.124	0	0.619	0	0	12.969
2018	7.236	5.172	0	0.717	0	0	13.125
2019	7.262	5.223	0	0.97	0	0	13.455
2020	7.241	5.122	0.025	1.191	0.01	0	13.589

2021	7.255	5.427	0.025	1.817	0.01	0	14.534
2022	8.189	5.538	0.025	2.817	0.025	0	16.594
2023	8.187	5.538	0.025	4.04	0.025	0	17.815
2024	8.347	5.583	0.025	5.808	0.03	0	19.793
2025	8.487	5.763	0.065	6.348	0.15	0.129	20.942
2026	8.627	5.943	0.105	6.888	0.27	0.258	22.091
2027	8.767	6.123	0.145	7.428	0.39	0.387	23.24
2028	8.907	6.303	0.185	7.968	0.51	0.516	24.389
2029	9.047	6.483	0.225	8.508	0.63	0.645	25.538
2030	9.187	6.663	0.265	9.048	0.75	0.774	26.687
2031	9.187	6.963	0.345	10.008	0.76	2.016	29.279
2032	9.187	7.263	0.425	10.968	0.77	3.258	31.871
2033	9.187	7.563	0.505	11.928	0.78	4.5	34.463
2034	9.187	7.863	0.585	12.888	0.79	5.742	37.055
2035	9.187	8.163	0.665	13.848	0.8	6.984	39.647
2036	9.187	8.463	0.745	14.808	0.81	8.226	42.239
2037	9.187	8.763	0.825	15.768	0.82	9.468	44.831
2038	9.187	9.063	0.905	16.728	0.83	10.71	47.423
2039	9.187	9.363	0.985	17.688	0.84	11.952	50.015
2040	9.187	9.663	1.065	18.648	0.85	13.194	52.607
2041	9.187	9.963	1.075	19.558	1.12	13.972	54.875
2042	9.187	10.263	1.085	20.468	1.39	14.75	57.143
2043	9.187	10.563	1.095	21.378	1.66	15.528	59.411
2044	9.187	10.863	1.105	22.288	1.93	16.306	61.679
2045	9.187	11.163	1.115	23.198	2.2	17.084	63.947
2046	9.187	11.463	1.125	24.108	2.47	17.862	66.215
2047	9.187	11.763	1.135	25.018	2.74	18.64	68.483
2048	9.187	12.063	1.145	25.928	3.01	19.418	70.751
2049	9.187	12.363	1.155	26.838	3.28	20.196	73.019

2050	9.187	12.663	1.165	27.748	3.55	20.974	75.287

Table C.9 – GW of Renewable Power Installed, Optimistic Scenario

Share of Final Exergy - BaU	Industry	Transport	Services	Residential	Agriculture/Forestry/Fishing	Energy industry own use
2017	27.14%	35.46%	11.10%	15.68%	2.78%	7.83%
2018	27.12%	35.68%	11.42%	15.99%	2.81%	6.98%
2019	27.33%	36.32%	11.12%	15.93%	2.86%	6.45%
2020	28.56%	32.90%	10.63%	17.96%	3.28%	6.67%
2021	28.46%	35.00%	10.42%	17.50%	3.37%	5.24%
2022	27.57%	36.01%	10.93%	16.41%	2.99%	6.08%
2023	25.94%	37.21%	15.30%	12.34%	2.33%	6.88%
2024	25.62%	37.43%	15.24%	12.52%	2.28%	6.92%
2025	25.29%	37.65%	15.18%	12.70%	2.23%	6.95%
2026	24.96%	37.87%	15.11%	12.88%	2.18%	6.99%
2027	24.63%	38.09%	15.05%	13.07%	2.13%	7.02%
2028	24.31%	38.31%	14.99%	13.25%	2.09%	7.06%
2029	23.98%	38.53%	14.93%	13.43%	2.04%	7.10%
2030	23.65%	38.75%	14.87%	13.61%	1.99%	7.13%
2031	23.33%	38.96%	14.81%	13.80%	1.94%	7.17%
2032	23.00%	39.18%	14.74%	13.98%	1.89%	7.20%
2033	22.67%	39.40%	14.68%	14.16%	1.84%	7.24%
2034	22.34%	39.62%	14.62%	14.34%	1.79%	7.28%
2035	22.02%	39.84%	14.56%	14.53%	1.75%	7.31%
2036	21.69%	40.06%	14.50%	14.71%	1.70%	7.35%
2037	21.36%	40.28%	14.44%	14.89%	1.65%	7.38%
2038	21.03%	40.50%	14.37%	15.07%	1.60%	7.42%
2039	20.71%	40.72%	14.31%	15.26%	1.55%	7.46%
2040	20.38%	40.94%	14.25%	15.44%	1.50%	7.49%
2041	20.05%	41.16%	14.19%	15.62%	1.46%	7.53%
2042	19.72%	41.37%	14.13%	15.80%	1.41%	7.56%
2043	19.40%	41.59%	14.06%	15.99%	1.36%	7.60%
2044	19.07%	41.81%	14.00%	16.17%	1.31%	7.64%
2045	18.74%	42.03%	13.94%	16.35%	1.26%	7.67%
2046	18.41%	42.25%	13.88%	16.53%	1.21%	7.71%
2047	18.09%	42.47%	13.82%	16.72%	1.16%	7.74%
2048	17.76%	42.69%	13.76%	16.90%	1.12%	7.78%
2049	17.43%	42.91%	13.69%	17.08%	1.07%	7.82%
2050	17.10%	43.13%	13.63%	17.27%	1.02%	7.85%

Table D.10 – Shares of Final Exergy across sectors, BaU Scenario

Share of Final Exergy - Optimistic	Industry	Transport	Services	Residential	Agriculture/Forestry/Fishing	Energy industry own use
2017	27.14%	35.46%	11.10%	15.68%	2.78%	7.83%
2018	27.12%	35.68%	11.42%	15.99%	2.81%	6.98%
2019	27.33%	36.32%	11.12%	15.93%	2.86%	6.45%
2020	28.56%	32.90%	10.63%	17.96%	3.28%	6.67%
2021	28.46%	35.00%	10.42%	17.50%	3.37%	5.24%
2022	27.57%	36.01%	10.93%	16.41%	2.99%	6.08%
2023	27.6%	35.4%	11.4%	16.6%	3.0%	6.0%
2024	27.6%	34.8%	12.0%	16.8%	3.0%	5.9%
2025	27.6%	34.1%	12.5%	17.0%	3.0%	5.8%
2026	27.6%	33.5%	13.0%	17.2%	3.0%	5.7%
2027	27.7%	32.9%	13.5%	17.4%	3.0%	5.6%
2028	27.7%	32.3%	14.0%	17.6%	3.0%	5.5%
2029	27.7%	31.6%	14.5%	17.8%	3.0%	5.4%
2030	27.7%	31.0%	15.0%	18.0%	3.0%	5.3%
2031	28.3%	30.2%	15.0%	18.2%	3.0%	5.3%
2032	29.0%	29.4%	15.0%	18.4%	3.0%	5.2%
2033	29.6%	28.6%	15.0%	18.6%	3.0%	5.2%
2034	30.2%	27.8%	15.0%	18.8%	3.0%	5.2%
2035	30.9%	27.0%	15.0%	19.0%	3.0%	5.2%
2036	31.5%	26.2%	15.0%	19.2%	3.0%	5.1%
2037	32.1%	25.4%	15.0%	19.4%	3.0%	5.1%
2038	32.7%	24.6%	15.0%	19.6%	3.0%	5.1%
2039	33.4%	23.8%	15.0%	19.8%	3.0%	5.0%
2040	34.0%	23.0%	15.0%	20.0%	3.0%	5.0%
2041	34.5%	22.6%	15.2%	19.8%	3.0%	5.0%
2042	34.9%	22.2%	15.4%	19.6%	3.0%	4.9%
2043	35.4%	21.8%	15.6%	19.4%	3.0%	4.9%
2044	35.8%	21.4%	15.8%	19.2%	3.0%	4.8%
2045	36.3%	21.0%	16.0%	19.0%	3.0%	4.8%
2046	36.7%	20.6%	16.2%	18.8%	3.0%	4.7%
2047	37.2%	20.2%	16.4%	18.6%	3.0%	4.7%
2048	37.6%	19.8%	16.6%	18.4%	3.0%	4.6%
2049	38.1%	19.4%	16.8%	18.2%	3.0%	4.6%
2050	38.5%	19.0%	17.0%	18.0%	3.0%	4.5%

Table D.11 – Shares of Final Exergy across sectors, Optimistic Scenario

Energy Carrier - BaU	Final Exergy Share			
	2017	2030	2040	2050
Industry				

Coal/Coke	6.9%	3.3%	0.6%	0.0%
Oil	7.8%	5.8%	4.1%	2.3%
Natural Gas	27.0%	30.6%	33.5%	35.4%
C.Renewables/Waste	26.2%	27.5%	28.1%	28.0%
Heat	2.3%	0.3%	0.0%	0.0%
Electricity	29.7%	32.4%	33.7%	34.2%
Transport				
Coal/Coke	0.0%	0.0%	0.0%	0.0%
Oil	94.7%	92.5%	91.5%	90.4%
Natural Gas	0.3%	0.7%	1.0%	1.3%
C.Renewables/Waste	4.4%	5.9%	6.4%	6.9%
Heat	0.0%	0.0%	0.0%	0.0%
Electricity	0.7%	0.9%	1.2%	1.5%
Services				
Coal/Coke	0.0%	0.0%	0.0%	0.0%
Oil	7.7%	6.4%	5.2%	3.9%
Natural Gas	13.9%	14.8%	16.1%	17.2%
C.Renewables/Waste	2.0%	0.6%	0.0%	0.0%
Renewables	1.9%	3.4%	4.5%	5.5%
Heat	0.8%	0.7%	0.7%	0.6%
Electricity	73.7%	74.2%	73.7%	72.8%
Residential				
Coal/Coke	0.0%	0.0%	0.0%	0.0%
Oil	16.8%	9.4%	3.6%	0.0%
Natural Gas	9.7%	11.3%	12.2%	12.9%
C.Renewables/Waste	31.4%	30.3%	29.9%	28.9%
Renewables	2.0%	3.0%	3.8%	4.5%
Heat	0.0%	0.0%	0.0%	0.0%
Electricity	40.1%	46.1%	50.5%	53.8%
Agriculture/Forestry/Fishing				
Coal/Coke	0.0%	0.0%	0.0%	0.0%
Oil	78.9%	80.6%	81.4%	81.8%
Natural Gas	1.3%	1.0%	0.7%	0.5%
C.Renewables/Waste	0.9%	0.6%	0.0%	0.0%
Heat	1.3%	0.7%	0.4%	0.1%
Electricity	17.7%	17.2%	17.4%	17.6%
Energy industry own use				
Coal/Coke	0.0%	0.0%	0.0%	0.0%
Oil	59.9%	64.6%	67.6%	69.5%
Natural Gas	8.1%	5.0%	1.7%	0.0%
Electricity	20.9%	17.3%	16.4%	15.2%
Heat	11.2%	13.1%	14.3%	15.3%

Table D.12 – Shares of Final Exergy, sectors across carriers, BaU Scenario

Energy Carrier - Optimistic	Final Exergy Share			
	2017	2030	2040	2050
Industry				
Coal/Coke	6.9%	0.21%	0.23%	0.23%
Oil	7.8%	0.18%	0.13%	0.10%
Natural Gas	27.0%	34.19%	24.75%	13.81%
C.Renewables/Waste	26.2%	15.19%	14.25%	11.52%
Renewables (Solar)	0.0%	0.73%	1.13%	2.93%
Heat	2.3%	15.15%	17.20%	12.45%
Electricity	29.7%	34.36%	42.31%	58.96%
Transport				
Coal/Coke	0.0%	0.00%	0.00%	0.00%
Oil	94.7%	79.80%	32.12%	5.77%
Natural Gas	0.3%	0.90%	2.36%	1.13%
C.Renewables/Waste	4.4%	7.73%	3.45%	0.55%
Electricity	0.7%	10.91%	50.66%	68.55%
Hydrogen	0.0%	0.65%	11.41%	24.01%
Services				
Coal/Coke	0.0%	0.0%	0.0%	0.0%
Oil	7.7%	3.7%	0.0%	0.0%
Natural Gas	13.9%	15.0%	8.0%	0.5%
C.Renewables/Waste	2.0%	1.4%	1.0%	0.5%
Renewables	1.9%	5.0%	8.0%	11.0%
Heat	0.8%	0.9%	1.0%	0.0%
Electricity	73.7%	74.0%	82.0%	88.0%
Residential				
Coal/Coke	0.0%	0.0%	0.0%	0.0%
Oil	16.8%	7.5%	0.0%	0.0%
Natural Gas	9.7%	16%	8.3%	1.0%
C.Renewables/Waste	31.4%	28%	16.6%	5.5%
Renewables	2.0%	5.0%	8.0%	10.9%
Heat	0.0%	0.2%	4.1%	0.0%
Electricity	40.1%	44.0%	63.0%	82.5%
Agriculture/Forestry/Fishing				
Coal/Coke	0.0%	0.0%	0.0%	0.0%
Oil	78.9%	57.8%	28.9%	0.0%
Natural Gas	1.3%	1.2%	1.6%	2.0%
C.Renewables/Waste	0.9%	1.7%	2.9%	4.0%
Heat	1.3%	1.4%	1.7%	2.0%
Electricity	17.7%	37.9%	65.0%	92.0%
Energy industry own use				
Coal/Coke	0.0%	0.0%	0.0%	0.0%
Oil	59.9%	49.7%	24.8%	0.0%
Natural Gas	8.1%	5.5%	4.7%	4.0%
Electricity	20.9%	38.2%	64.1%	90.0%

Heat	11.2%	6.7%	6.3%	6.0%

Table D.13 – Shares of Final Exergy, sectors across carriers, Optimistic Scenario

Efficiencies (Final-to Useful Ex)	2017	2030	2040	2050
Coal/Coke				
Fuel - HTH	46.79%	49.96%	51.33%	52.71%
Fuel - MTH	26.34%	28.02%	28.76%	29.50%
Fuel - LTH1	19.53%	20.75%	21.29%	21.83%
Fuel - LTH2	14.95%	15.87%	16.27%	16.67%
Fuel - LTH3	8.80%	9.37%	9.63%	9.89%
Steam locmt	0.00%	0.00%	0.00%	0.00%
Oil				
HTH	46.79%	49.84%	51.19%	52.54%
MTH	26.34%	28.02%	28.76%	29.50%
LTH1	19.53%	20.75%	21.29%	21.83%
LTH2	14.95%	15.87%	16.27%	16.66%
LTH3	8.80%	9.37%	9.63%	9.89%
MW1 (Aviation)	30.94%	30.94%	30.94%	30.94%
MW2 (LPG/Gasoline)	10.09%	10.12%	10.14%	10.15%
MW3 (Oil SMD & Diesel)	12.61%	12.65%	12.67%	12.69%
Diesel-elect v (rail)	25.33%	29.16%	31.07%	32.98%
Navigation	39.56%	42.25%	43.71%	45.17%
Natural Gas				
HTH	46.79%	46.86%	46.90%	46.95%
MTH	26.34%	26.37%	26.39%	26.41%
LTH1	19.53%	19.55%	19.57%	19.58%
LTH2	14.95%	14.96%	14.97%	14.98%
LTH3	8.80%	8.81%	8.82%	8.83%
NatGas vehicles	8.00%	8.00%	8.00%	8.00%
MW3 (SMD)	39.56%	40.36%	40.89%	41.42%
C. Renewables/Waste				
HTH	46.79%	49.84%	51.19%	52.54%
MTH	26.34%	28.02%	28.76%	29.50%
LTH1	19.53%	20.75%	21.29%	21.83%
LTH2	14.95%	15.87%	16.27%	16.66%
LTH3	8.80%	9.37%	9.63%	9.89%
MW3(diesel)	13.02%	13.25%	13.43%	13.62%
MW3 (smd)	40.99%	40.99%	40.99%	40.99%
MW2 lpg/gasol	10.42%	10.60%	10.75%	10.90%
Navigation	40.99%	40.99%	40.99%	40.99%
Heat (CHP, Solar thermal, Geothermal)				
HTH	46.79%	49.84%	51.19%	52.54%
MTH	26.34%	28.02%	28.76%	29.50%

LTH1	19.53%	20.75%	21.29%	21.83%
LTH3	8.80%	9.37%	9.63%	9.89%
Hydrogen (FCEV)				
Light vehicles	52.50%	63.33%	71.67%	80%
Heavy vehicles	47.50%	58.33%	66.67%	75%
Electricity - Industry/Energy Industry own use	74.81%	80.61%	87.38%	90.00%
Electricity - Transport	87.71%	90.00%	90.00%	90.00%
Electricity - Residential	17.11%	20.20%	20.24%	22.01%
Electricity - Services	17.12%	20.20%	20.25%	22.02%
Electricity - Agriculture/Forestry/Fishing	74.81%	80.61%	87.38%	90.00%

Table E.14 – Efficiencies

Aggregate Efficiency	BaU Scenario	Optimistic Scenario
2017	23.50%	23.50%
2018	23.31%	23.31%
2019	23.07%	23.07%
2020	23.33%	23.33%
2021	23.01%	23.01%
2022	22.99%	22.99%
2023	23.85%	24.95%
2024	23.85%	25.88%
2025	23.84%	26.79%
2026	23.84%	27.67%
2027	23.84%	28.51%
2028	23.83%	29.31%
2029	23.83%	30.09%
2030	23.82%	30.82%
2031	23.81%	32.53%
2032	23.80%	34.18%
2033	23.81%	35.77%
2034	23.81%	37.30%
2035	23.82%	38.78%
2036	23.83%	40.22%
2037	23.85%	41.61%
2038	23.87%	42.95%
2039	23.91%	44.24%
2040	23.95%	45.50%
2041	23.99%	46.69%
2042	24.03%	47.89%
2043	24.10%	49.09%
2044	24.17%	50.11%
2045	24.26%	51.09%
2046	24.36%	52.07%

2047	24.48%	53.04%
2048	24.55%	53.99%
2049	24.58%	54.94%
2050	24.62%	55.88%

Table E.15 – Aggregate Efficiencies