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STUDENT REPORT

Title:

Sustainable utilization of biomass-derived fuels in the Greek industry by 2050

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Abstract:

Under current plans, the EU aims to be climate-neutral by 2050. However, its industrial sector – which makes up nearly a quarter of its total energy consumption – still faces significant technical and institutional barriers to decarbonization.

This study uses Greece as a case study to investigate the role of biomass and biomass-derived fuels in achieving a future carbon-neutral industrial sector in line with EU targets. This study uses IndustryPLAN and a methodology which includes interviews and a literature review to create different scenarios regarding the future industrial fuel mix in Greece. These scenarios specify the demand that can be covered by biomass fuels or electricity, depending on the required process temperatures.

The results of this investigation are integrated into the EnergyPLAN, and the final evaluation of the future scenarios considers the remaining sections of the Greek energy system.

The evaluation shows that high electrification alone does not reduce biomass consumption in contrast to hydrogen use; higher use of dry biomass leads to better economic results. The preferable scenario investigated in this study is one that combines electrification, dry biomass, and gaseous biomass combustion. It is the preferable scenario because it offers fuel flexibility and limits biomass consumption and overall costs.

In contrast, scenarios which use gaseous electrofuels as an alternative to biomass can decrease biomass consumption but increase system costs.

The study concludes that there are feasible alternatives to decarbonize the Greek industrial sector while keeping biomass consumption at a sustainable level.

Preface

This report constitutes a master thesis and was written within the framework of the 4th semester of the master's program Sustainable Energy Planning & Management. The report was written between February 2023 and May 2023.

I would like to especially thank my supervisor Brian Vad Mathiesen for all the constructive ideas and guidance he gave me during this project. His knowledge and experience inspired me and broadened my horizons in sustainable energy planning.

Furthermore, I would like to thank David Maya-Drysdale and Rasmus Magni Johannsen, employees of Aalborg University for the time dedicated to explaining to me the Greek energy models in IndustryPLAN and EnergyPLAN.

I would like also to thank all the employees of the private companies that share their knowledge regarding renewable fuels and the Greek industrial energy system and contributed to a more realistic project based on real-life conditions.

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Nomenclature

BAT	Best Available Technology
CA	Choice Awareness
CAPEX	Capital expenditure
CEEP	Critical excess electricity production
CHP	Combined heat and power
EE	Energy efficiency
ETS	Emissions trading system
HP	Heat pump
LNG	Liquified natural gas
OPEX	Operational expenditure
PP	Power plant
PV	Solar photovoltaics
RE	Renewable energy
RES	Renewable energy sources
SCC	Social cost of carbon
VRES	Variable renewable energy sources

Definitions

Sustainable biomass future potential

This study focuses on keeping biomass utilization in Greece at a sustainable level. The term sustainable means that the bioenergy chains can be functional infinitive, that biomass is grown domestically (with its use increasing energy security and decreasing dependency on fossil fuels imports from foreign countries), does not compete with food and the country's share of worldwide sustainable biomass level (the quantity of biomass that the country can use without undermining the fulfilment of other countries' CO_2 targets) is not exceeded. (IEA, 2020; Lund et al., 2022; Reijnders, 2006)

The Greek population is estimated to be approximately 10.632.000 people by the year 2050 (European Commission, 2005). According to Lund et al., (2022), the sustainable biomass energy resources per capita will be 27-33 GJ/capita by 2050. In the sEEnergies project, (2023) the biomass consumption is 21,8 GJ/capita. These estimations vary due to different studies and policies assumed, for example, policies regarding the increase of forest lands.

Considering the above numbers, the annual biomass consumption for the total Greek population is between 64,38 to 97,46 TWh. By restricting bioenergy exploitation according to global availability, Greece will be a part of a sustainable global solution. Lund et al., (2022) In general, sustainable scenarios lead to fewer bio sources and biomass production and more available agricultural land (Ruiz et al., 2019). In this study, the biomass use will be restricted to 64 TWh.

Biogas and biomethane

Biogas is a mix of CH_4 and CO_2 that is produced through anaerobic digestion of different biomass sources like sewage sludge, animal, and farming by-products, residential biowaste and energy crops. Biomethane is the upgraded biogas to meet natural gas standards. (European Biogas Association (EBA), 2019)

Syngas and bioSNG

Syngas is produced through solid biomass gasification (wood chips, dried biowaste, etc.) and can be upgraded to bioSNG with a methanation step. (European Biogas Association (EBA), 2019)

90% of the green gas worldwide meeting natural gas standards (biomethane, bioSNG) comes from biogas (IEA, 2020). For the purposes of this study, both biomethane and bioSNG are referred to as biomethane as in the report of (Alberichi et al., 2022).

Electrofuels

Electrofuels are the fuels that derive when electricity is transformed into chemical energy in the form of fuel. This study considers only renewable electrofuels (biomass-to-electrofuel or emissions-to-electrofuels) (Ridjan et al., 2016). The electrofuels used in this study are e-methane or liquid electrofuels which are used in the transport sector. E-methane is produced when hydrogen, produced through electrolysis is methanized. Power to methane uses CO_2 streams, for example, biogas upgrade, and combines it with green hydrogen. (European Biogas Association (EBA), 2019) A similar process is followed for liquid electrofuels production.

According to Lester et al., (2020), electrofuels that use biomass as a carbon source are more economical when using carbon capture. For this reason, in this study, power to methane using biomass carbon sources is prioritized against power to methane using carbon capture where is possible.

Bio-LNG

Bio-LNG is produced when biomethane is liquified (Lam et al., 2022). In this study, biomethane consists of gas that meets natural gas characteristics, and it is produced from renewable sources.

The social cost of carbon

SCC is an indicator of the present detrimental damage of carbon emissions in society. It also is an estimate of the benefit of any action taken to reduce a ton of carbon emissions.

It aims to reduce GHG emissions, through investments and change of behavior, to a level that SCC equals the extra cost of managing the emissions. This is done by setting an impost for every tone emitted above the free allocations given in the energy sector. Higher SCC means that more expensive investments can be done in a cost-effective way (the benefits of the policy outweigh the costs and it pays for itself in the long run). (Pearce, 2003)

Sequential crops

Sequential cropping is the farming of two or more crops in the same field and in the same farming year (*Sequential Multiple Cropping*, 2017). When done properly, it offers many benefits to the economy and public health. It can lead to sustainable biogas production with no land use change and the production of organic fertilizer as a by-product which benefits the soil. Fewer fertilizer expenses and the production of biogas offer a new income to farmers, helping them to stabilize the price of their agricultural goods (EBA, 2020). Different crops can be used in the biomass gasification process (Sikarwar et al., 2016).

1 Introduction

1.1 Energy transition and European industry

Nowadays, Europe has two major reasons to convert its current energy system to a more sustainable energy system (supply & demand). The first is to achieve energy security with a short-term focus on terminating its dependence on Russian energy sources, and the second is to deal decisively with the climate crisis. In the short-term, the EU is addressing these issues by trying to diversify its fossil fuel energy sources, but its main targets in the long term are the improvement of energy efficiency and the development of renewables. Moreover, high expectations exist for the industrial sector (European Commission, 2022). The European industrial sector is responsible for 23% of the total final energy demand, but its decarbonization has not been sufficient. Many barriers, such as the remaining lifetime of existing facilities, insufficient knowledge, privacy in energy data and technical difficulties due to the complexity of the different industrial processes, have led to this outcome. (Johannsen et al., 2023)

The European ETS is an instrument invented to decrease GHG emissions cost-effectively and promote innovation measures in energy-consuming sectors including industry (Gasbarro et al., 2013). The ETS system also includes industry sectors which are at risk of carbon leakage. These industries could leave the EU due to high environmental cost and produce in countries with looser emission restrictions, violating the environmental and economic benefits of the EU (European Commission, 2019). Currently, for the decade 2021-2030, for these sectors at the highest risk of carbon leakage, the CO_2-free allocations are based on a benchmark operation of the most efficient installations (*Allocation to Industrial Installations*, n.d.). However, from October 2023, the EU will test the Carbon Border Adjustment Mechanism (CBAM) which will be fully operating from 2026. Products that are carbon intensive and are imported from countries with fewer emission restrictions will have an extra carbon tax. (SARIO, 2022) This theoretically will replace and reduce the importance of the free allowances concept which is used to protect the EU from carbon leakage (Taylor & Romano, 2022). By limiting the free allowances, European industries which are not focusing on a carbon-free future, will have to pay for the emitted CO_2. Without investing in limiting CO_2, increased emissions could hinder their competitiveness (Gasbarro et al., 2013) due to higher taxation expenditures. This fact presents an opportunity for great energy-related investments in the European industry without the danger of industries leaving the EU.

On top of that, European countries have filed national plans for 2030, strategy plans for 2050 and climatic laws to ensure that these plans are going to be accomplished.

1.2 Energy transition in Greece

This study focuses on Greece as a case study for energy planning in the industry, which, during this climate and energy crisis time, is full of investment potential. In 2020, Greece filed a document analyzing the long-term strategy for 2050 supplementary to the national climate and energy plan for 2030. Greece relies on natural gas to decrease its GHG emissions but in the long term, it is agreed that it must be replaced by carbon-neutral gasses (such as biomethane produced from wet and dry biomass), e-methane from Power-to-X, and green hydrogen from electrolysis, where the remaining natural gas demand has to be supplemented by CO_2 capture.

For the Greek industry, the first step is to increase energy efficiency and material recycling (Ministry of Environment and Energy, 2022), because these technologies are available and more cost-efficient (Kermeli et al., 2022). Moreover, electrification of the industrial processes is playing a significant part in ongoing decarbonization (Kermeli et al., 2022).

On the other hand, there are some issues identified regarding the decarbonization of Greek industry and Greece in total. It is important that electricity consumed directly or used for electrolysis originates from RES because currently, 46% of industrial CO_2 emissions are resulting from electricity needs. (Kermeli et al., 2022) Furthermore, biomass which is a direct substitute for fossil fuels in all forms has to be distributed in all energy sectors and not surpass sustainable levels to achieve a national and global energy system free of fossil fuels. (Lund et al., 2022)

These are only two of the reasons why it is crucial that any analysis done in the industrial or other energy sector must be integrated into the rest of the country model. When transitioning to a 100% renewable energy system, better decisions are made when they include all energy sectors (Korberg et al., 2020). In this study, the focus is on the Greek industrial sector, but the results are integrated into the rest of the Greek energy system, as described in subchapter 2.3.

1.3 Relevant research and latest studies

Many relevant projects are evaluating green transition in the industry in combination with the rest of the country's energy system. One of them, which forms the main inspiration of this study is the SEEnergies project (Maya-Drysdale et al., 2022). SEEnergies' main target is to combine cost-effective energy efficiency measures in buildings, transport, and industrial energy sectors with hour-by-hour RE models and spatial analysis. It aims for a 100% RE system having in mind 2030 targets and independence from Russian fossil fuels. The energy consumption and the overall costs are lower than other previous estimations due to energy efficiency and synergies between the energy sectors which lead to better utilization of RE and the lowest investments in energy conservation. (sEEnergies project, 2023)

The final scenario of the project regarding Greece in 2050, sEEnergies 1.5 scenario, combines economically feasible energy efficiency measures (BAT and innovative measures), electrification, renewable energy investments and hydrogen and biomass use which lead to a 100% renewable energy scenario. That scenario stipulates that global warming will stay below 1,5 °C compared to pre-industrial levels. With some modifications that scenario is used in this study. Ideas are drawn from its methodology, the energy models for Greek industry and Greece and the assumptions that surround them.

Another document which is used extensively in this study is the *Long-term Strategy Document for 2050* from the Greek government. It includes actual data for 2015 and estimations about 2050 regarding the country's and industry's fuel mix, biomass utilization and the energy and climate goals of the Greek government (Ministry of Environment and Energy, 2022).

Lund et al., (2022) helped to specify what types of biomass sources are evaluated in the study and gave inspiration about the term sustainable biomass potential and how to specify it.

Münster & Lund, (2009, 2010) proved that biogas and syngas are better options than the incineration of the same waste. Based on that, biomass resources utilized in the industry are evaluated mostly as gaseous fuels. In addition, Hakawati et al., (2017) state that the energy efficiency production of biomethane is similar to biogas but with significant advantages like easier transportation and more applications. This study only considers gases that compete with natural gas in their characteristics and are suitable for all industrial processes.

Finally, Korberg et al., (2020) mention that e-methane is the most expensive option when compared to biomethane and syngas. Therefore, where possible, these fuels are prioritized in the scenarios.

1.4 Focus and delimitations of the study

This study specifies the Greek biomass potential in 2050 based on the literature review and gives a more realistic view of fuel usage and fuel mix in the Greek industrial sector. Based on the above, it also examinates scenarios about how this potential should be utilized in the industrial sector and nationally.

The study does not look into the Greek transport & building sectors or energy grids. These parts of the energy system are included in the Greek energy model fixed from previous 2015 and 2050 models about Greek energy systems in EnergyPLAN from the sEEnergies project.

The study also does not include solar thermal in the technical solutions. According to Thiel & Stark, (2021), this technology can reach 565 C° it has low energy density and requires significant infrastructure, which needs further investigation in order to fit in the space of an industry.

1.5 Research question

This subsection includes the research question of the study which elaborates the main problem, and it is the reference point for the upcoming analysis. The given sub-questions will guide that analysis and contribute to answering the research question. The four sub-questions are the following:

SQ1: What is the future biomass potential of Greece?

SQ2: Which mix of industrial fuels should Greece use by 2050?

SQ3: How do changes in industrial fuel mix technically affect the Greek energy system?

SQ4: How do changes in industrial fuel mix economically affect Greek society?

The research question is:

How can the Greek industry exploit sustainable biomass and feasible substitute fossil fuels by 2050?

The following specifies the meaning of the keywords of the research question and the sub-questions.

The term **feasible** could have different meanings in each study. Therefore, it is analyzed in subchapter 2.2.1.

The term **technically** includes fuel consumption, biomass consumption, imports and CEEP.

CEEP is the critical excess energy production and describes the situation where electricity production is higher than its demand, storage and export capacity. RE systems should be turned down before this situation happens otherwise the system is in danger of collapsing. Therefore, RE systems' capacity factor is reduced alongside the economic feasibility of the energy system. (Lund, 2014a)

The term **economically** includes the annualized fuel and investment cost in the industry, and overall annualized costs of the Greek energy system.

2 Methodological framework

This chapter describes the theoretical approach behind this study and the methodology focusing on answering the Research question.

2.1 Theoretical framework

The main theory applied in this study is the choice awareness theory (CA) as formulated by Lund, (2014b) and focuses on radical technological changes. The technology consists of five different dimensions, technique, knowledge, organization, product and profit. If more than one dimension changes then the technological change is characterized as radical (Lund, 2014b). When trying to decarbonize the industrial sector, the way energy is produced and distributed (technique), the needed knowledge, the organizations involved and the individuals making profit change. The product which is electricity, heat and cooling, stays the same. Therefore, industrial sector decarbonization is a radical technological change.

The goal of this study is to raise awareness of public and private organizations and show that there are feasible choices to achieve climate neutrality. This, with some reservation due to uncertainty in the cost and the development of renewable technology, is the goal of the Greek government (Ministry of Environment and Energy, 2022). The Greek government aims to use limited quantities of gas in industry, buildings and electricity production and capture CO_2 emissions (Ministry of Environment and Energy, 2022). However, these actions do not ensure its energy security because it still meets fuel demands with imported fuel. The alternatives proposed in this study aim to overcome that barrier. CA can be raised through the following strategies (Lund, 2014b):

Strategy 1: Design concrete technical alternatives. This strategy is described in par. Scenarios development and implemented in the subchapters 3.2 and 3.3. The alternatives should cover the same demand, have similar costs to the existing system and their benefits (energy security, less emissions) should be pointed out.

Strategy 2: Design a socioeconomic feasibility study. This step is described in sub-chapter 2.2.1.

Strategy 3: Introduce public measures and regulations discussed in chapter 6. This step aims to also make the investments feasible from a business perspective.

Strategy 4: Implement new democratic infrastructure discussed in chapter 6. The final step focuses on identifying the organizations that will contribute to the implementation of this study.

2.2 Methods

Following 2.1 the goal of this sub-chapter is to give details about the methods and tools used in the report.

2.2.1 Feasibility study

This feasibility study is inspired by Hvelplund & Lund, (1998), which specifies 3 steps of performing such a study.

The first step is defining what is studied, for whom and why (www-analysis). The scope of this study includes the examination of the technical (3.2, 3.3), economic (4), and social feasibility (3.3.2) of the replacement of the fossil fuels used in the Greek industry with biomass-derived fuels. The term 'social feasibility' examines the impact (biomass consumption) of the study on society; for example, limiting biomass consumption for domestic energy purposes may lead to more biomass available for other uses (exports, furniture). The time horizon is 2050, the year that the Greek government has committed to be carbon neutral (Ministry of Environment and Energy, 2022) and long, more than 20 years. This means, however, that some parameters should be investigated in the context of a sensitivity analysis (4.2.2). Furthermore, this study aims to give a clear view of the existing potential and how the transition should be done. The results can be used by the EU, the Greek government or can supplement the work of other researchers. Moreover, industries can be advised from the results to make sustainable energy policies. The study is relevant now due to the environmental and energy crisis which forces governments to accelerate the transition to green energy and to improve their energy security. It can be concluded that the study is socioeconomic as it aims to identify solutions which benefit society as a whole.

The second step in the feasibility study is to define the way the study is realized and its consequences. It considers the Greek government's environmental and sustainability goals (1.1), alongside economic and renewable energy resources (Sustainable biomass future potential). Furthermore, as a socioeconomic feasibility study, it considers the imports and exports of biomass and energy and excludes taxes. The economic resources are considered by keeping the overall energy system's cost at levels similar to current and future Greek government scenarios (4.2.1).

The third step refers to the implementation of the feasibility study, and it is described in detail in the next subchapter 2.3.

The results of the feasibility study and its sensitivity analysis are discussed in chapter 5.

2.2.2 Data collection

Extensive data collection was carried out for the purposes of this study.

Interviews

In the context of this study, the following interviews were conducted. Interviews contribute to the addition of value to the report and add new scientific data which can further be used in other studies.

- Aalborg University employees (Rasmus Magni Johansen, David Maya-Drysdale).

The goal of this communication was to understand the assumptions behind the 2015 and 2050 energy models about Greece and the Greek industry in EnergyPLAN and IndustryPLAN respectively. More specifically, it was specified where the data used comes from, assumptions regarding the future fuel mix and step-by-step discussion about the mitigation measures implementation.

- BlueGrid (BlueGrid, 2023)

The main target of this interview was to collect data about bio-methane and bio-LNG potential and cost in Greece. This interview added significant knowledge to the study by sharing documents regarding biomethane utilization and potential in the EU and relevant EU directives (Alberichi et al., 2022; European Biogas Association, 2022; Renewable Energy Directive, 2018). BlueGrid also shared data regarding CAPEX, OPEX and efficiency of biomethane infrastructure and raw material costs. More details can be found in subchapter 8.1.

- Greek industries

The industries were asked for data regarding the needed process temperatures. Each industry is a representative example of the sectors that IndustryPLAN divide the total industrial energy demand (chemicals, iron and steel, non-ferrous metals, non-metallic minerals, paper and pulp, food & beverage) and the data collection is based on limited interviews (see subchapter 8.2).

Literature review

The literature review is used primarily to collect data for the analysis and secondarily to draw inspiration for theories and methodology sub-chapters (2.1, 2.2). When a subject is described in this study, there is an effort to ensure that the data occurs from different sources in order to ascertain its value. How and where this method is used in the analysis are described in detail in subchapters 1.3 and 2.3.

In general, the papers used are prioritized according to the year published as most of the technologies evaluated here are under development. Technical and cost features can change year by year. In addition, the most recent governmental and EU documents are investigated as they aggregate different knowledge (technical, spatial analysis, economical) and show the identified potential and the latest future projections regarding renewable energy sources. Recent documents also show the current problems that need urgent action and ensure this study is relevant and useful. Furthermore, material focusing on Greece is preferred, as Greece is the main subject of the study. Danish papers are the next choice as Denmark is a frontrunner in RE: Denmark has the highest share of biogas in gas composition (Korberg et al., 2020) and in renewable energy planning and sets an example for the rest of the EU.

In addition, the literature review helps to specify the current and biomass potential of Greece (see subchapter 3.1). Greek government documents like the *Greek National Energy and Climate Plan and Long-term strategy for 2050* (HELLENIC REPUBLIC et al., 2019; Ministry of Environment and Energy, 2022) alongside EU reports (Ruiz et al., 2019) are used to form a comparison scenario for the future biomass potential (Sustainable biomass future potential). Many sources were used to garner ideas on how to proceed to the next steps of the analysis and to shape baseline and future scenarios.

2.2.3 Scenarios development

This subsection analyses the process of designing the different scenarios in this study and it is based on the methods used in (Kermeli et al., 2022).

The first scenario is the baseline scenario for the Greek industry in 2015 (3.2.1). 2015 is the year used as a baseline scenario in IndustryPLAN and in the long-term strategy document of the Greek government.

The process of designing the future scenarios for the Greek industry is described and applied step by step in sub-chapter 3.2.2. All future scenarios are based on the maximum use of recycled materials and the implementation of energy efficiency measures as described in Table 14 in 3.2.2 and in compliance with the principle that energy efficiency comes first (Kermeli et al., 2022; Maya-Drysdale et al., 2022).

Finally, the scenarios about the total Greek energy system result from the energy model created in EnergyPLAN within (sEEnergies project, 2023) with some modifications described in 3.3.1. All scenarios regarding the Greek industry are integrated into the 2050 Greek energy model to identify the best scenario for Greece as a whole and avoid that industry decarbonization leads to a system that is not optimal (sEEnergies project, 2023).

2.2.4 Economic analysis

LCOE

This indicator points to the average cost per unit of energy generated from an energy system component considering the discounted costs (Kästel & Gilroy-Scott, 2015). The annual costs used in the LCOE calculation are calculated as follows (Lund & Thellufsen, 2021):

- Annualized Investment cost of investment$_x$ (Ainvc$_x$)

  Ainvc$_x$ = $(Total\ investment_x\ cost)\ * i/[1-(1+i)]^{-n}$

- i is the interest rate
- n is the lifetime of the investment

- Annual fixed operational costs (Afc$_x$)

  Afc$_x$ = P$_x$* $Total\ investment_x$ cost

- P$_x$ is the annual fixed operation and maintenance costs (% of the total investment cost)

- Annual variable operational costs (Avc$_x$)

Annual fixed operational costs of units used in electricity balancing.

- Annual fuel costs (Afc$_x$)

Annual fixed fuel costs include fuel market prices and handling costs Wind turbine LCOE is calculated to specify the cost of electricity and used in 4.1.1.

Sensitivity analysis

This part of the analysis shows how different parameters influence the results of the analysis and more specifically the LCOE. The sensitivity analysis aims to include in the study that biomass is a scarce resource, and its value is not reflected usually by its price. For this reason, the analysis repeated for some scenarios aiming to lower biomass resources utilization (4.2.2).

2.2.5 Tools

This sub-section includes the tools used for creating and processing the data used in the analysis.

Excel

This software is used for numerous calculations and data processing. All the data in subchapter 3.1 and all the results from IndustryPLAN and EnergyPLAN are processed in Excel. The tool is also used for illustrations.

IndustryPLAN

IndustryPLAN is a tool developed in Excel and offers the possibility to study European or national industry sectors in the context of the green transition. It bridges the gap between national-level analyses and site-specific individual analyses in industry. The software is used in this study for developing future Greek industrial demand assuming specific energy efficiency, electrification and fuel substitution measures. The output of the software is used as an input in EnergyPLAN (see below). IndustryPLAN prioritizes recycling scenarios, Best Available Technologies (BAT) and innovative measures. Then, the electrification of different industrial processes and the shift to the use of hydrogen-based or biomass fuels. Finally, the excess heat used in district heating systems and the heat pumps needed for that purpose. (Johannsen et al., 2022).

The exact level of mitigation measures implemented and how the results are utilized in EnergyPLAN is analyzed in 3.2.

EnergyPLAN

Many tools analyze the integration of renewable energy in national energy systems (Connolly et al., 2010). This specific software is chosen in the study for two main reasons.

The first is that it is designed mainly for supplementing the formation of national policies which is the main scope of this study. It simulates the operation of national energy systems, both technically and economically. It combines the electricity, heating, cooling, industrial and transport sector, making annual analyses in hourly steps. Moreover, it includes various mature and under-development technologies, which fulfill the needs of this study. (Lund & Thellufsen, 2021).

The second reason is that it is easy to integrate the industry sector energy model (using IndustryPLAN) into the rest of the Greek energy system, as described above. As mentioned in 1.2, the analysis is done in an individual energy sector, in this case, the industrial, that should be integrated into the rest of the Greek energy system. The implications of such integration should be defined.

To sum up, in this case, the model is used for understanding how a complex energy system of the Greek industry can be sustainable and understand how changes in it affect the rest of the Greek energy system. (Lund & Thellufsen, 2021). The simulation is done technically which means that the tool identifies the least fuel-consuming operation of the energy system. The economic evaluation is done in later parts of the analysis in Excel. Since, the study considers energy security as one of its objectives, electricity imports and exports are limited, as described in 3.3.

2.3 Research design

The purpose of the research design sub-chapter is to make a clear step-by-step description of the process followed to answer the research question.

Steps of the analysis	Method/ Tool used
3.1 Biomass utilization	
3.1.1 Current biomass (biogas, wooden biomass, waste, energy crops) utilization in Greece (TWh).	Interviews Literature review Interviews
3.1.2 Future biomass potential utilization in Greece.	
3.1.3 Bioenergy use per sector, current and future. Define how much biomass is needed for the rest of Greece (electricity production, transportation, heating & cooling) in 2050.	
3.2 Scenarios regarding Greek industry	
3.2.1 Identification of the Greek industrial fuel demand (2015). 3.2.2 Identification of the future fuel demand in industry after the application of some mitigation measures (material recycling, best available techniques) in IndustryPLAN. Identification of fuels that could substitute the remaining fossil fuels based on the process temperatures per sector and the natural gas distribution grid. 3.2.3 Comparison of the scenarios.	Literature review IndustryPLAN EnergyPLAN
3.3 Future scenarios regarding the Greek energy model and biomass consumption	
3.3.1 Integration of industry scenarios to the 2050 Greek energy model to understand how it is affected. Transport, electricity, heating and cooling sector have the same demand as in the sEEnergies' 1,5 scenario. 3.3.2 Detailed analysis of the biomass use in each scenario.	EnergyPLAN
4 Evaluation part of the analysis	
4.1 & 4.2.1 Cost analysis (investment, fuel). Calculation of the cost difference between sustainable scenarios and the 2015 model.	EnergyPLAN IndustryPLAN Excel Interviews
4.2.2 Sensitivity analysis (How is the Greek energy system affected, technically and economically by reduced biomass availability)	EnergyPLAN Excel

Table 1: Research design of the study

3 Analysis

In the main Analysis part of this study, three of the four sub-questions are answered in the following steps:

- SQ1 in 3.1
- SQ2 in 3.2
- SQ3 in 3.3

3.1 Biomass utilization

The purpose of this subchapter is to specify the biomass exploitation for energy purposes in Greece.

3.1.1 Current biomass utilization in Greece

As it is described in 2.3 the first step is to estimate the biomass quantities used for energy purposes in Greece. The Greek strategy report regarding energy and climate in 2050 (Ministry of Environment and Energy, 2022) includes data about biomass usage in Greece in 2015 which are combined with data in sEEnergies project, (2023). The outcome is presented in Table 2 and Table 3.

Biomass Raw material	**TWh**
Imported wood	2,21
Waste	4,53
Wooden biomass (logging)	0,12
Agricultural residues	9,3
Energy crops	4,95
Total	**21,11**

Table 2: Biomass raw materials

Final use of biomass	**TWh**
Biofuels (1st generation)	1,98
Biogas	1,51
Waste incineration	0,29
Households/ Industry dry wooden biomass	11,33
Total	**15,11**

Table 3: Final use of biomass consumption in 2015

Waste resources are considered to be transformed partially in biogas and a small amount is incinerated for electricity production. Most of the dry biomass is consumed in the residential sector and the rest of it is in the industry. Energy crops are transformed into biofuels with an efficiency of 40% (sEEnergies project, 2023).

Table 4 shows the analysis of biogas sources in Greece based on (European Biogas Association, 2022) for 2021 as the total amount of biogas for this year is similar to the amount identified by (Ministry of Environment and Energy, 2022) in the year 2015. Before 2020 some data was not included in the report (European Biogas Association, 2022). The category 'Other' is considered to be agricultural residues as it includes biogas that is utilized for self-consumption and industrial heating purposes.

Biogas sources	TWh	Comments
Landfill	0,65	
Sewage	0,07	
Industrial	0,02	
Agricultural	0,42	Agricultural residues
	0,02	Sequential crops
	0,03	Energy crops
Other (Self-consumption/ Industrial heating)	0,31	Agricultural residues
Total biogas:	**1,51**	

Table 4: Biogas sources in Greece

3.1.2 Future potential for biomass utilization in Greece

(Ministry of Environment and Energy, 2022) also includes two different energy system scenarios for Greece which aim to contribute to the Paris Agreement target to limit temperature increase below 1,5 °C compared to the preindustrial levels. The first one is based on the deployment of hydrogen and e-fuels and the second one is based on energy efficiency (EE) and extensive electrification. The projected biomass raw material development in these two scenarios is presented in Table 5. Part of wooden biomass is gasified to biomethane. In future scenarios, there is no farming that competes with the food chain. (Ministry of Environment and Energy, 2022)

Biomass raw materials	H_2 and e-fuels	EE and Electrification
	TWh	TWh
Imported wood	4,88	7,67
Waste	10,00	10,23
Wooden biomass (logging)	0,93	1,40
Agricultural residues	17,33	18,14
Energy crops (sequential crops & wooden biomass)	21,51	28,84
Total	54,65	66,28
Total without imports	**49,77**	**58,60**

Table 5: Greek government scenarios about biomass raw material in 2050

In both scenarios, the total domestic biomass consumption is lower than the sustainable biomass consumption for energy purposes in Greece as described in par. (**Sustainable biomass future potential)** if the imports are excluded. As a result, the quantities in Table 5 can be used for further calculations. Moreover, in this study, it is assumed that the biomass raw materials will be closer to the higher predictions, (58,6 TWh).

Alberichi et al., (2022) include projections for biogas and biomethane potential in European countries. It considers strict sustainability criteria and includes wastes and residues, sequential crops but no energy crops. Additional feedstocks that are not examined in this study are biomass from marginal or contaminated land, seaweed and landfill gas (Alberichi et al., 2022; European Commission, 2022). All the values are in billion cubic meters (bcm) and are converted to TWh multiplied by 10,7. The projected quantities for Greece are presented in Table 6.

Biomethane production process	bcm	TWh
Anaerobic digestion	2	21,40
Thermal gasification	0,65	6,96
Total	**2,65**	**28,36**

Table 6: Greek biomethane potential in 2050

Based on assumptions in sEEnergies project, (2023), biomethane production efficiency from anaerobic digestion is 100% (with some limited consumption of electricity) and from biomass gasification is 81% biomethane and 5 % heat. Following that the results from each biomethane production technology are presented in Table 7 and Table 8.

Resource	Raw material (TWh)	Electricity consumed (TWh)	Biomethane quantity (TWh)
Sequential crops	12,31	0,07	12,31
Animal manure	1,93	0,01	1,93
Agricultural residues	5,78	0,03	5,78
Industrial wastewater	1,39	0,01	1,39
Total	21,41	0,12	21,41

Table 7: Main quantities of biomethane produced from anaerobic digestion in 2050.

Resource	Raw material (TWh)	Biomethane quantity (TWh)	Heat (TWh)
Wood waste	0,87	0,7	0,04
Forestry waste	0,61	0,49	0,03
Municipal solid waste	3,88	3,13	0,19
Landscape care wood	2,16	1,74	0,11
Prunings	1,12	0,9	0,06
Total	8,63	6,96	0,43

Table 8: Main biomethane resources from thermal gasification in 2050

Then, by extracting the biomass resources used for biomethane (Table 5, Table 7, Table 8), the biomass raw material available for other uses is specified in Table 9.

Biomass Raw material	Total available	Without biomethane resources
	TWh	TWh
Waste	10,23	4,96
Wooden biomass (logging)	1,4	1,4
Agricultural residues	18,14	5,68
Energy crops (sequential & wooden biomass)	28,84	16,53
Total	58,61	28,57

Table 9: Biomass raw material after the subtraction of resources used for biomethane.

3.1.3 Current and future biomass utilization by sector

This subchapter is made to present the predicted use of biomass in different energy sectors first by the Greek government and then by Aalborg University's researchers. This data is evaluated to better understand where the available biomass specified in subchapter 3.1.2 should be used. Table 10 includes the present (2015) and future (in both scenarios described in subchapter 3.1.2) biomass consumption in every energy sector according to the (Ministry of Environment and Energy, 2022). It also includes wooden biomass imports, so the total biomass consumption is higher than the one presented in Table 5.

Biomass consumption per sector	**2015**		**H_2 and e-fuels**		**EE and Electrification**	
	TWh	**%**	**TWh**	**%**	**TWh**	**%**
Industry	2,91	18%	6,86	12%	6,74	10%
Refineries	0,00	0%	2,91	5%	2,21	3%
Electricity production	1,05	7%	25,47	45%	22,33	34%
Shipping	0,00	0%	2,91	5%	6,16	9%
Trains	0,00	0%	0,00	0%	0,00	0%
Aviation	0,00	0%	7,33	13%	16,16	24%
Road transport	1,74	11%	4,42	8%	10,12	15%
Total transport	**1,74**	**11%**	**14,65**	**26%**	**32,44**	**49%**
Buildings and Farming	10,35	64%	6,86	12%	2,56	4%
Total	**16,05**	**100%**	**56,74**	**100%**	**66,28**	**100%**

Table 10: Biomass consumption per energy sector.

In 2015, the main amount of biomass was utilized in the buildings and farming sector, followed by industry and transport. In future scenarios, the Greek government aims to swift priority to transportation in the high electrification scenario and to electricity production in the e-fuels scenario. The industry is in third place in both future scenarios. The high electrification scenario exploits approximately 10 to 12 TWh more biomass than the e-fuels scenario, as it has higher needs in the sectors where electrification is not possible. The utilization of H_2 and electrofuels reduces biomass consumption so they will be further assessed.

In the EnergyPLAN model (sEEnergies project, 2023) made by Aalborg University's researchers and where the Greek energy system analysis is based (see subchapter 2.2.3), the sustainable biomass potential utilized in Greece in 2050 is estimated as follows in Table 11.

Use of biomass	**TWh**
Individual heating (Dry biomass)	1,2
Waste incineration in CHP	7,6
Gasified biomass (gas & electrofuels)	24,5
Biogas (Upgraded to biomethane)	3,59
Additional Electricity & Heat production (Dry biomass)	7,91
Industry (Dry biomass)	5,1
Total Biomass consumption	**48,7**

Table 11: Biomass consumption per use in Greece in 2050.

In the EnergyPLAN model, there are no second-generation biofuels. All fuels needed for heavier transportation and aviation are produced as liquid electrofuels, partially from gasified biomass and H_2. The rest of the gasified biomass is upgraded to bioSNG and injected into the grid. The waste input burned in CHP for 2050 in EnergyPLAN is considered high as waste is not referred to as fuel in the electricity sector (Ministry of Environment and Energy, 2022).

In subchapter 3.3. it is described how the quantities in Table 11 change to meet the Greek energy demand for every scenario in the Greek industry (subchapter 3.2.2) considering the Sustainable biomass future potential specified in this study (Table 5, Table 9).

3.2 Scenarios regarding Greek industry

The target of this subchapter is to specify the industrial fuel demand in 2050.

3.2.1 Baseline analysis - Greek industry fuel demand

Based on the IndustryPLAN model of Greece on the sEEnergies project, Eurostat and Greek long term strategy document (*Final Energy Consumption in Industry by Type of Fuel*, 2023; Ministry of Environment and Energy, 2022; sEEnergies project, 2023) the fuel demand of the Greek industry is as illustrated in Figure 1.

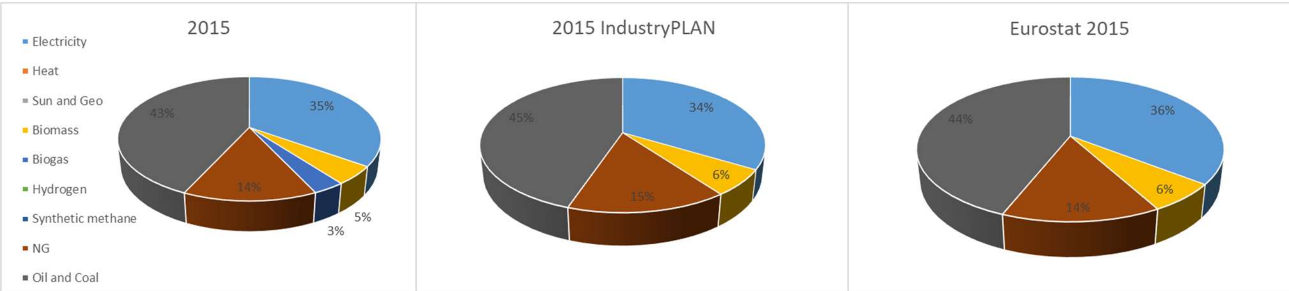

Figure 1: Greek industrial fuel demand in 2015

To specify the baseline scenario for this study (Table 12), the average values for each type of fuel are chosen. The Ministry of Environment and Energy, (2022) states that Greek industry utilizes 1,21 TWh of biogas but this value is rejected as high, considering that in 2015 biogas production was 1,51 TWh (see subchapter 3.1.1) and the vast amount of it is used for electricity production (European Biogas Association, 2022).

Baseline 2015	**TWh**
Oil and Coal products	16,05
Electricity	12,66
Natural gas	5,26
Biomass	2,12
Biogas	0,4
Total energy consumption	**36,49**

Table 12: Baseline scenario for Greek industry in 2015

3.2.2 Future Greek industry's fuel demand

In (Ministry of Environment and Energy, 2022) document there are two future scenarios regarding industrial fuel demand in 2050 which are described in Table 13 and Figure 2. These scenarios are presented for comparison with the final scenarios of this study in subchapter 3.2.3.

Fuel	H_2 and e-fuels 2050	EE and Electrification 2050
Electricity	17,12	17,43
Biomass	5,1	4,59
Biogas	1,77	2,1
NG	0,47	2,56
Heat	0,64	0,58
Sun and Geo	0,37	0,24
Oil & Coal	0,05	0,07
Hydrogen	3,2	0
E-methane	2,22	0
Total energy consumption (TWh)	**30,93**	**27,58**

Table 13: Long-term strategy scenarios regarding the Greek industry

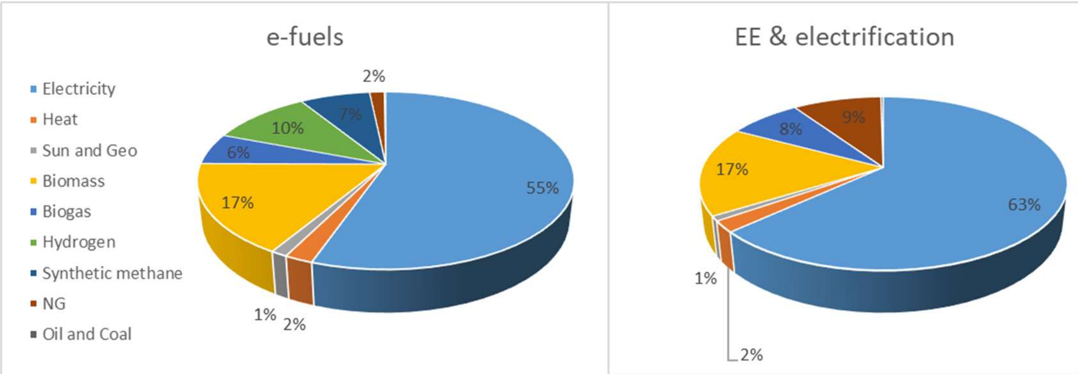

Figure 2: Long-term strategy scenarios regarding the Greek industry

As shown in Table 13, future industrial energy demand is estimated between 27,58 TWh and 30,93 TWh.

The same level of energy consumption is predicted in IndustryPLAN taking into account sEEnergies project data.

More specifically, in a frozen efficiency scenario, the total energy consumption in the Greek industry by 2050 is 46,08 TWh. The fuel consumption is higher due to the rise in the GDP development (sEEnergies project, 2023) and simultaneously maintaining the same energy intensity as the 2015 system (Johannsen et al., 2023). Implementing high material recycling leads to a decreased fuel demand of 44,67 TWh (sEEnergies project, 2023) and on top of that, the 100 % application of energy efficiency measures (best available technologies & innovative measures) further reduces the energy demand to 30,82 TWh.

This scenario is the base for all the future scenarios for the Greek industry created in this study. The results of this process are illustrated in Table 14.

Scenario	Frozen efficiency	High recycling	Energy efficiency
Fuel	**TWh**	**TWh**	**TWh**
Coal	2,51	2,51	1,74
Peat	0	0	0
Oil	10,06	9,49	5,77
NG	4,04	4,02	2,77
Geothermal	0	0	0
Biomass	12,68	12,54	8,28
Heat	0,9	0,87	0,57
Electricity	15,89	15,24	11,69
Hydrogen	0	0	0
Total	**46,08**	**44,67**	**30,82**

Table 14: Greek industry fuel demand on a frozen efficiency, a high recycling scenario and a 100% energy efficiency implemented scenario.

IndustryPLAN defines also the energy demand for each industrial sector. The most significant energy consumer in the Greek industry is the 'Others' sector which includes the food industry followed by non-ferrous metals and non-metallic minerals (Table 15).

Fuel/ Sub-sector	Chemicals	Foundries	Iron and steel	Non-ferrous metals	Non-metallic minerals	Paper and pulp	Others	Total
Coal	0,00	0,00	0,00	1,72	0,01	0,00	0,00	1,74
Peat	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Oil	0,05	0,00	0,05	0,00	3,38	0,07	2,22	5,77
NG	0,13	0,00	0,03	1,70	0,14	0,17	0,60	2,77
Geothermal	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Biomass	0,50	0,00	0,04	1,70	1,97	0,16	3,91	8,28
Heat	0,02	0,00	0,00	0,16	0,17	0,01	0,21	0,57
Electricity	0,69	0,00	1,00	3,05	0,93	0,41	5,61	11,69
Hydrogen	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Total	**1,40**	**0,00**	**1,12**	**8,32**	**6,60**	**0,82**	**12,55**	**30,82**

Table 15: Fuel demand by sector in an energy efficiency scenario by 2050.

This fuel demand (except Heat & Electricity) is substituted by renewable fuels (gaseous or solid) or electricity.

The energy source that can be used in the industrial sector is defined by the process temperatures required. These temperatures are specified from the interviews (see subchapter 8.2) and the literature review (see subchapter 8.3). There is an assumption that the percentage of energy consumption in the different temperatures stays the same in 2050. The results are shown in Table 16.

Temperature (°C)	T<180	180<T<250	250<T<1000	1000< T < ∞	Total energy consumption/ Electricity consumption/ Heat
Sub-sectors/ example	**%**	**%**	**%**	**%**	**TWh**
Chemicals		22%	12%	9%	1.4/ 0,69/ 0,02
Foundries	0	0	0	0	0/0/0
Iron and steel	Already electrified			At least 62%	1.12/1/0
Non-ferrous metals/ aluminium company	Limited	Limited	Around 1000 almost all of the energy demand		8.32/3,05/0,16
Non-metallic minerals/ glass company			5%	95%	6.6/0,93/0,17
Paper and pulp/ paper company	5%		95%		0.82/0,41/0,01
Others/ food company	40%		60%		12.55/5,61/ 0,21
Total					**30,82/ 11,69/ 0,57**

Table 16: Allocation of the energy demand of each sector to different temperature levels.

Jiang et al., (2022) state that industrial heat pumps can reach temperatures up to 144,5 **°C** with COP of 5,3 and (Thiel & Stark, 2021) state that currently industrial heat pumps can generate heat at 180 **°C** but they have the potential for 280 **°C**. According to Buhler et al., (2019) HPs in temperatures between 180 **°C** to 220 **°C** have a COP of 1,5. Moreover, Roelofsen et al., (2020) claim that industrial processes (<1000**°C**) can be electrified in the present and do not require a significant change in the way the process is made. Usually, they can be electrified using an electric boiler or a furnace. Industrial processes >1000 **°C** may be electrified in the future. Electric boilers and furnaces have similar efficiencies to the ones that use fossil fuels (Pee et al., 2018).

Considering the previous paragraph as well as Table 15 and Table 16 the non-electrified energy demand can be substituted by the technologies presented in Table 17.

Prioritized technologies	HP (COP=4)	HP (COP=1,5)	El. Boilers/ furnaces or dry biomass	Green gasses
Temperature (°C)	**<180**	**<250**	**<1000**	**< ∞**
Sub-sectors	**TWh**	**TWh**	**TWh**	**TWh**
Chemicals	0,1	0,31	0,17	0,13
Iron and steel	0	0	0	0,12
Non-ferrous metals	0	0	1,53	3,58
Non-metallic minerals	0	0	4,15	1,10
Paper and pulp	0,01	0	0,22	0,06
Others	2,41	0	3,62	0,67

Table 17: Energy demand that is substituted by different fuels considering the temperature of the industrial process.

Hydrogen and biomass can replace fuels and some fuels used as feedstocks (Pee et al., 2018). Regarding hydrogen usage in the industrial sector, Korberg et al., (2023) state that hydrogen can slightly benefit the industrial sector and reduce the usage of biomass at more economic costs. Hydrogen will be an important energy carrier for the production of e-fuels (Korberg et al., 2023).

In this study, gaseous fuels are prioritized against dry biomass (see Table 20). Dry biomass has much lower energy density and lower combustion temperature than coal and fuel oil. The first characteristic leads to increased fuel transport and handling costs (Thiel & Stark, 2021). Furthermore, supplying industries with large quantities of dry biomass is challenging (Ministry of Environment and Energy, 2022) and even not possible.

Furthermore, for very high temperatures the use of H_2 requires a redesign of furnaces and safety considerations (Pee et al., 2018). On the other side, green gases identical to methane do not require discarding existing investments that with proper maintenance have a lifetime of 50 years (Pee et al., 2018). In the next scenarios, H_2 is used mostly as a component to create methane.

It is assumed that processes which change from coal, oil and dry biomass to gaseous fuels succeed a higher fuel efficiency of 10% (see differences in Table 17 & Table 18). Finally, in 2021, gas consumption was 33% of the total non-electric consumption (*Final Energy Consumption in Industry by Type of Fuel*, 2023). It is also assumed that industries using coal and oil products are not connected to the natural gas grid. Gas networks are located in cities where strict environmental rules do not allow such fuels. It assumed that, in the future, 50 % of the non-electric fuel consumption will be in industries connected to the natural gas distribution grid. In all scenarios, the gas substituting fossil fuels and dry biomass should be 50% liquified (see Table 20).

After specifying the available fuels, their characteristics and the needed process temperatures for the industrial sector, alternative scenarios are examined regarding fuel substitution.

More specifically:

- <u>Scenario 1</u> the energy demand in processes 250 °C<T<1000 °C is electrified.
- <u>Scenario 2</u> the energy demand in processes 250 °C<T<1000 °C is covered by dry biomass.

The final energy demand of each sector in scenarios 1 and 2 are presented in Table 18 and Table 19 accordingly.

Sub-sectors	**Previous electricity demand**	**New electricity demand (after fuel substitution Table 17)**	**Heat**	**Dry biomass**	**Green gasses**
	TWh	**TWh**	**TWh**	**TWh**	**TWh**
Chemicals	0,69	0,40	0,02	0	0,12
Iron and steel	1	0,00	0	0	0,11
Non-ferrous metals	3,05	1,53	0,16	0	3,34
Non-metallic minerals	0,93	4,15	0,17	0	1,10
Paper and pulp	0,41	0,22	0,01	0	0,06
Others	5,61	4,23	0,21	0	0,67
Total	**11,69**	**10,52**	**0,57**	**0,00**	**5,41**

Table 18: New energy demand per industrial sector, scenario 1.

Sub-sectors	Previous electricity demand	New electricity demand (after fuel substitution from Table 17)	Heat	Dry biomass	Green gasses
	TWh	**TWh**	**TWh**	**TWh**	**TWh**
Chemicals	0,69	0,23	0,02	0,17	0,12
Iron and steel	1	0,00	0	0	0,11
Non-ferrous metals	3,05	0,00	0,16	1,53	3,34
Non-metallic minerals	0,93	0,00	0,17	4,1477	1,10
Paper and pulp	0,41	0,00	0,01	0,2166	0,06
Others	5,61	0,60	0,21	3,6216	0,67
Total	**11,69**	**0,84**	**0,57**	**9,69**	**5,41**

Table 19: New energy demand per industrial sector, scenario 2.

Further scenarios for the decarbonization of the industrial sector can be examined via IndustryPLAN as follows:

- Scenario 100% el: applying 100% electrification.
- Scenario 3: applying 100% electrification and “green” methane for fuel substitution for the rest of the non-electric energy demand.
- Scenario 4 applying 100% electrification and “green” methane and dry biomass for fuel substitution for the rest of the non-electric energy demand.
- Scenario 5: applying two more steps, 100% application of hydrogen use where it is possible and swift of the remaining fossil fuels to dry biomass. Scenario 5 is the one used in (sEEnergies project, 2023)

The fuel allocation in all scenarios is presented in following Table 20.

The 100% electrification scenario is not further evaluated as it includes fossil fuels and it presented for auxiliary purposes.

Fuel	Scenario 1	Scenario 2	100% electrification	Scenario 3	Scenario 4	Scenario 5
Electricity	22,21	12,53	15,63	15,63	15,63	15,88
Heat	0,57	0,57	0,38	0,38	0,38	0,16
Dry biomass	0	9,69	5,22	0	5,22	5,13
Hydrogen	0	0	0	0	0	3,01
Biomethane/ Synthetic methane	2,71	2,71	0	5,67	3,33	0
BioLNG	2,71	2,71	0	5,67	3,33	0
Coal	0	0	1,57	0	0	0
Oil	0	0	3,36	0	0	0
Natural gas	0	0	2,21	0	0	0
Total	**28,20**	**28,21**	**28,37**	**27,35**	**27,89**	**24,18**

Table 20: Scenarios regarding Greek industrial fuel demand after fuel substitution.

3.2.3 Comparison of the scenarios regarding future Greek industrial demand.

As presented in Table 13, the Greek government aims to use some fossil fuels by 2050, mostly natural gas in the EE & electrification scenario. It aims to achieve climate neutrality with CO_2 capture maintaining some energy dependency (see 2.1). In the H_2 and e-fuels scenario in which green gaseous fuels are available, the fossil fuel usage drops to less than 1 TWh. The dry biomass use in both scenarios is similar and the electricity production is higher in the scenarios that IndustryPLAN creates (scenarios 3,4 & 5). (Ministry of Environment and Energy, 2022).

Scenario 2 has the lowest electricity consumption and the highest dry biomass consumption. Scenario 3 has the highest gas fuel consumption. Moreover, scenario 5 has the lowest fuel consumption without considering the electricity needed for H_2 production.

3.3 Future scenarios regarding the Greek energy system

In this step, the fuel demand of the industry is integrated into the 2050 Greek energy model in EnergyPLAN to understand which scenario is better for Greece as a whole and avoid industry decarbonization leading to a system that is not optimal as described in 2.2.3.

3.3.1 Future Greek system's fuel demand

The sEEnergies Greek energy model about 2050 in EnergyPLAN considers the 100% el & H_2 scenario in the industry (scenario 5 in Table 20) (Lund & Thellufsen, 2021). It is displaced for comparison together with the 2015 model of Greece. The rest of the scenarios are modified, as waste incineration in CHP is replaced by biomass (dry and gaseous) combustion. Biomass resources are also changed. The scenarios in EnergyPLAN are named with the names of the industry scenarios (Table 20) they include. Additionally, sEEnergies models (2015 & 2050) consider higher imports and exports of electricity. In this study imports of electricity are limited approximately to 0,5 TWh and CEEP at 4,5 TWh. The final results can be seen in Table 21.

	2015	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	sEEnergies 2050
Total fuel consumption (TWh)	231,52	149,81	147,23	147,45	146,96	141,42	144,77
Electricity production (TWh)	48,02	118,32	108,67	111,78	111,75	116,14	115,08
VRES electricity (%)	30%	80%	82%	82%	82%	80%	86%
PP & CHP electricity (%)	70%	20%	18%	18%	18%	20%	14%
Industry (fuel input/ Heat) (TWh)	20,26/0	5,41/0,57	11,34/0,57	11,34/0,38	11,88/0,38	8,14/0,16	8,14/0,16
Electricity imports (TWh)	9,61	0,51	0,45	0,53	0,53	0,48	4,49
Electricity for industry (TWh)	12,7	22,21	12,53	15,63	15,63	15,88	15,88
Fixed Import/ Export (TWh)	-9,61	0	0	0	0	0	0
Natural gas imports (TWh)	30,76	0	0	0	0	0	0,48
Biomass (TWh)	15,24	59,64	59,85	60,10	59,5	58	48,76
Waste Input in CHP (TWh)	0,29	0	0	0	0	0	7,6
Electricity for H_2 (TWh)	0	24,66	24,66	24,66	24,66	28,96	28,94
Biomethane from biomass gasification (injected into the grid) (TWh)	0	17,31	11,28	18,86	14,16	11,86	19,76
Biomethane or biogas from anaerobic digestion (injected into the grid) (TWh)	1,06	21,4	21,4	21,4	21,4	21,4	3,59
CEEP/ Exports (TWh)	0,19	4,47	4,5	4,52	4,52	4,52	7,43

Table 21: Greece energy model results

Comments on Table 21 figures:

- in all scenarios, the biomass needed is less than the 64 TWh specified in the (par. Sustainable biomass future potential).
- Scenario 5 has the lowest fuel consumption and the second highest electricity production.

- The utilization of H_2 in the industry increases energy efficiency and VRES integration. This leads to less biomass combustion which is less efficient (45% to 55% electric efficiency).
- Scenario 1 has the largest electricity consumption as it includes higher industry electrification. This fact does not reduce biomass consumption significantly.
- There is a limit to the electricity that can be produced from VRES without additional storage investments.
- Higher electricity consumption needs higher biomass consumption to avoid CEEP.

The conclusion is that higher use of H_2 may further reduce biomass consumption without increasing CEEP (scenario 5/ electricity for H_2).

3.3.2 Future use of biomass in Greece

In Table 22 is presented the bioenergy usage per energy sector and final use for the five scenarios.

Bioenergy consumption per Energy sector (TWh)	**Final use**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
Individual heating	Dry biomass	1,20	1,20	1,20	1,20	1,20
Transport	Liquid e-fuels	3,60	3,60	3,60	3,60	3,60
Industry	Dry biomass	0,00	9,69	0,00	5,22	5,13
Heat and Power	Dry biomass	11,10	9,09	9,64	9,63	11,09
Industry	Biomethane (Gasified biomass)	3,63	2,95	9,51	4,25	0,00
	Biomethane (upgraded biogas)	3,48	4,25	8,40	4,93	0,00
Heat and Power	Biomethane (Gasified biomass)	18,70	11,91	14,74	14,18	15,57
	Biomethane (upgraded biogas)	17,93	17,16	13,01	16,48	21,41
Total		**59,64**	**59,85**	**60,10**	**59,49**	**58,00**

Table 22: Bioenergy direct usage per sector in 2050.

Comments on Table 22 figures:

- Part of the gasified biomass is transformed into liquid electrofuels with the addition of H_2.
- CHP and power plants consume 62% to 83% and industry consumes 9% to 30% of the demand.
- The transport sector consumes 6% and individual heating 2%. (See Figure 3 below).
- The industry and transport sector also consume bioenergy indirectly through electrification.
- 18% to 20% of the electricity is produced in PP or CHP which consumes biomass in a dry or gas form (Table 21/PP & CHP electricity)

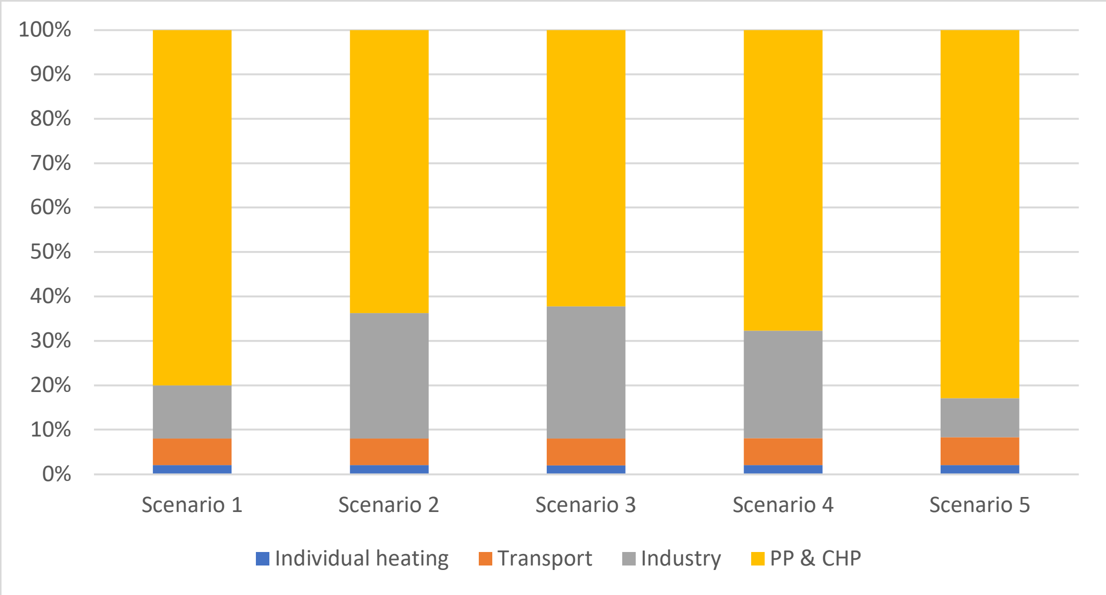

Figure 3: Bioenergy consumed by sector.

Furthermore, considering Table 9 and Table 22, there is a need for additional wooden biomass than the biomass specified by the Greek government in Table 5. The additional dry biomass needed in each scenario is presented in Table 23.

Biomass raw material	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Additional dry biomass needed (TWh)	5,99	6,2	6,45	5,85	4,35

Table 23: additional biomass raw material needed.

The remaining waste source (estimated as 4,96 TWh /Table 9) cannot be utilized further as waste incineration is not considered in this study and all the waste potential that can be turned into biomethane is already used (see Table 7). The additional biomass should be either imported, or the Greek local biomass production should rise. In the case of biomass imports, further studies should be carried out to determine how it will economically affect Greek society and how much it will affect the energy supply security of Greece.

In subchapter 4.2.2 additional technical scenarios are examined to investigate how the utilization of e-methane could affect biomass consumption. Scenario 3 has the highest biomethane consumption which derives from biomass gasification and the highest overall biomass consumption. Scenario 2 has the second highest biomass consumption alongside the highest dry biomass consumption in the industry (see Table 21). In these scenarios, the partial replacement of biomethane with e-methane will be further examined.

4 Evaluation part of the analysis

In the evaluation part of the Analysis of this study, sub-question 4 is answered. The scenarios evaluated are both regarding the Greek industry and Greece.

- SEEnergies 2015
- Scenario 1
- Scenario 2
- Scenario 3
- Scenario 4
- Scenario 5

Each variable of the evaluation is annualized.

4.1 Greek industry

4.1.1 Fuel costs

Electricity cost for 2050 is based on the LCOE of an onshore wind turbine as described in 2.2.4. and for 2015 (European Commission, 2015). Similarly, hydrogen cost derives from electricity cost combined with electrolysis and H_2 storage costs extracted from the model in (sEEnergies project, 2023). The H_2 price used in this report is higher when compared to the price of 30 €/MWh (Furfari, 2021). Heat cost is assumed to be 20% lower than the cost of producing it from biomass. Biomass cost is based on data from (sEEnergies project, 2023). Biogas, bioLNG and biomethane costs come from the interview in 8.1 (O. Rigopoulos, personal communication, April 13, 2023). Fossil fuels cost applies only for 2015 as 2050 models are not utilizing fossil fuels (Aizarani, 2023; HAEE, 2021; *Interview with Employees in Greek Industry*, personal communication, 2023; TRADING ECONOMICS, 2023). As described in 2.2.1, the feasibility study is socioeconomic so all the taxes are excluded and all fuel handling costs are taken from (sEEnergies project, 2023).

Fuel	**(€/MWh)**	**(€/MWh)**
Year	**2015**	**2050**
Electricity	80	29,71
Heat	-	19,89
Dry biomass	25,39	24,86
Hydrogen	-	63,12
Biomethane/Synthetic methane	-	70,24
BioLNG	-	90,24
Biogas	60	55
Coal	15	-
Oil	27,78	-
Natural gas	30,19	-

Table 24: Fuel prices including handling costs.

The fuel cost of each scenario results from Table 20 and Table 24. The result can be found in Table 25.

Fuel cost (M€)	2015	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Electricity	1.013	660	372	464	464	472
Heat	-	11	11	8	8	3
Dry biomass	54	-	241	-	130	128
Hydrogen	-	-	-	-	-	190
Biomethane/Synthetic methane	-	190	190	398	234	-
BioLNG	-	245	245	512	300	-
Biogas	24	-	-	-	-	-
Coal	33	-	-	-	-	-
Oil	375	-	-	-	-	-
Natural gas	159	-	-	-	-	-
Total	1.658	1.106	1.059	1.382	1.136	792

Table 25: Annual fuel cost of each scenario regarding the Greek industry.

In 2015, Greek society paid more for fuel consumption in the industry. Scenario 3 has the higher fuel costs among future scenarios due to the high use of biomass-derived gaseous fuel) and scenario 5 has the lowest due to less fuel use.

4.1.2 Investment cost

The investment cost is based on data received from IndustryPLAN. For future scenarios, BAT and Innovative measures investments are the same as described in 3.2.2. For Scenario 3, Scenario 4 and sEEnergies 2050 the cost of 100% electrification arises also from IndustryPLAN. Based on electrification cost (euro/ $TWh_{substituted}$) the costs for electrification are specified in Scenario 1 and Scenario 2. For Scenario 2 the final cost is decreased by 20%, to take into account that the first amount of processes that are electrified are cheaper and it is increased by 20% for Scenario 1 to take into account the opposite fact according to sEEnergies project, (2023). Finally, regarding sEEnergies 2050 scenario, the cost of switching in H_2 is included from sEEnergies project, (2023). All the results are in Table 26.

Investment cost (M€)	2015	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
BAT	0	1.065	1.065	1.065	1.065	1.065
Innovative measures	0	167	167	167	167	167
Electrification	0	385	21,83	128	128	128
H_2 utilization	0					97
Total	**0**	**1.616,94**	**1.253,83**	**1.360,41**	**1.360,41**	**1.457,81**
Annualized investment cost		**108,68**	**84,28**	**91,44**	**91,44**	**97,99**

Table 26: Investment cost of each scenario.

Scenario 1 is the most expensive due to higher electrification followed by scenario 5 which includes H_2 turn costs. Scenario 2 has the lowest investment costs.

4.1.3 Comparison of fuel and investment cost in Greek industry.

The annual costs of each scenario are in Table 27.

Annual costs	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
(M€)	1.214,77	1.143,64	1.473,27	1.227,51	890,47

Table 27: Total annual cost of each scenario.

Scenario 3 is the most expensive mostly due to higher fuel costs followed by scenario 4.

4.2 Greek energy system

This subchapter refers to the economic feasibility of the system regarding Greece as a whole.

4.2.1 Costs

The EnergyPLAN cost analysis results for the future scenarios and 2015 are presented in Table 28 and Table 29. The 2015 results are presented for informational reasons to understand which is the difference in energy costs that Greek people should pay for energy. In all scenarios including bioLNG in the industry sector, an additional cost of the bioLNG is added.

Annual costs (M€)	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Gasoil/ Diezel	46	46	46	46	46
Petrol/ JP	11	11	11	11	11
Gas handling	103,85	97,85	177,75	116,4	32
Biomass	1844	1928	1844	1879	1849
Total fuel costs	**2.005**	**2.083**	**2.079**	**2.052**	**1.938**
Marginal operation costs	92	81	84	84	92
Total electricity exchange costs	1	1	1	1	1
Total variable costs	**2.098**	**2.165**	**2.164**	**2.137**	**2.031**
Fixed operation costs	5.440	5342	5383	5368	5412
Annual investment costs	25.046	24834,15	24927,25	24887,6	24974
Total annual costs	**32.584**	**32.341**	**32.474**	**32.393**	**32.417**

Table 28: EnergyPLAN cost analysis for the different 2050 scenarios.

Scenario 1 (highest EE) has the highest investment and overall costs. Scenario 5 (H_2) has the lowest fuel costs but the second higher investment costs. Scenario 2 with the least electrification in the industry has the lowest overall costs. Scenario 3 with the highest gaseous fuels has the highest fuel costs.

In Table 29, it presented the total annual costs of the Greek energy system in 2015.

Annual costs (M€)	2015
Coal	481
Fuel oil	17
Gasoil/ Diezel	2158
Petrol/ JP	0
Gas handling	57
Biomass	687
Total fuel costs excl NG	**3.400**
NG exchange costs	1.030
Marginal operation costs	172
Total electricity exchange costs	2182
Total variable costs	**6.784**
Fixed operation costs	2.150
Annual investment costs	10.892
Total annual costs	**19.826**
CO2 Net (Mt)	55,43

Table 29: EnergyPLAN cost analysis for 2015.

The system costs less than two third of the future scenarios including a CO_2 price per ton of 42. Rennert et al., (2022) estimate a cost of 185 dollars per ton taking into account more recent projections, climate models and methods. This difference can add a social cost of 7.150 million euros annually. The total cost of 2015 for Greek society including social costs was 26.976 million euros. This leads to a cost difference between 2015 and 2050 scenarios of 5.365 to 5.608 million euros.

4.2.2 Sensitivity analysis

As specified in 3.3.2, in the part of the sensitivity analysis, it is examined how the partial replacement of biomethane with e-methane can affect biomass consumption and the economics of the Greek energy model. Scenario 3 has the highest biomethane consumption which derives from biomass gasification and the highest overall biomass consumption (see Table 21). Scenario 2 has the second highest biomass consumption alongside the highest dry biomass consumption in the industry (see Table 22).

Scenarios after the changes are called e-fuel scenarios. The technical results for scenarios 2 & 3 and scenarios $2_{\text{e-fuel}}$ & $3_{\text{e-fuel}}$ can be seen in Table 30. The economic results are in Table 30.

Fuel consumption (TWh)	Scenario 3	Scenario 3 e-fuel	Difference	Scenario 2	Scenario 2 e-fuel	Difference
Total	154,09	154,48	-0,39	152,07	151,83	0,24
RES electricity	85,11	92,56	-7,45	83,34	89,98	-6,64
Power plants	17,06	15,59	1,47	15,68	14,09	1,59
CHP	3,4	2,84	0,56	3,45	3,02	0,43
Electricity imports	0,53	0,51	0,02	0,45	0,51	0,06
Biomass	60,10	53,05	7,05	59,85	52,97	6,88
Electricity for H_2	24,66	30,30	-5,64	24,66	29,55	-4,89
Biomethane from biomass gasification (injected into the grid)	17,31	6,93	10,38	11,28	0,46	10,82
Biomethane or biogas from anaerobic digestion (injected into the grid)	21,4	21,4	0	21,4	21,4	0
E-methane injected into the grid	0	9	-9	0	7,8	-7,8
CEEP/ Exports	4,52	4,52	0	4,5	4,51	0,01

Table 30: Scenario 3 and e-fuel technical differences

As can be seen in Table 30 the fuel consumption in both existing and new scenarios is similar. Although in Scenario 3 3-fuel scenario there is a small increase while in scenario 2 and scenario $2_{e\text{-}fuel}$ a small decrease. RES electricity production is much higher as more electricity is needed to produce e-methane in both e-fuel scenarios. The CEEP stays the same as the electrolyzer capacity and the hydrogen capacity is much bigger in e-fuel scenarios. This leads to better utilization of CEEP. Power plant and CHP energy production are higher in scenario 2 and 3 as less variable RES are utilized. Moreover, the electricity consumption for H_2 is higher in the e-fuel scenarios. The biomethane derived from biomass gasification is much less in the e-fuel scenarios as it is the overall biomass consumption. The biomass needed in the e-fuel scenarios is less than the biomass raw material specified by the Greek government in Table 9 (53,65 TWh) when the remaining waste potential (4,96 TWh) is removed.

Annual costs (M€)	Scenario 2	Scenario 2 e-fuel	Difference	Scenario 3	Scenario 3 e-fuel	Difference
Gasoil/ Diezel	46	46	0	46	46	0
Petrol/ JP	11	11	0	11	11	0
Gas handling	98	95	3	178	175	3
Biomass	1928	1726	202	1844	1637	207
Total fuel costs	**2083**	**1878**	**205**	**2079**	**1869**	**210**
Marginal operation costs	81	75	6	84	78	6
Total electricity exchange costs	1	1	0	1	1	0
Total variable costs	**2165**	**1954**	**211**	**2164**	**1948**	**216**
Fixed operation costs	5342	5481	-139	5383	5512	-129
Annual investment costs	24834	25047	-213	24927	25164	-237
Total annual costs	**32.341**	**32.482**	**- 141**	**32.474**	**32.624**	**- 150**

Table 31: Scenario 3 and e-fuel economic differences

From Table 31, the e-fuel scenario is 150 million euros more expensive annually than scenario 3. The fuel cost falls as biomass consumption is reduced. On the other hand, operation (fixed and variable) costs rise alongside investment costs. The same happens in scenario 2.

To summarize, scenarios 2 and 3 have the highest biomass consumption in all the scenarios. This shows that a big drop in biomass consumption can be achieved through e-fuel use with a higher annual cost.

5 Discussion of the results

The following chapter discusses the results of the previous analysis and the evaluation part of the analysis chapters. It aims to conclude with a preferable technical scenario among the rest of the scenarios regarding the future energy transition of the Greek industry.

The first notable result of the previous analysis is that when comparing the difference between the annual costs of each scenario in the industrial sector, with the ones in the Greek system (Table 27 & Table 28) the conclusion is different. For instance, when studying only the industrial sector (Table 27), scenario 5 has the lowest annual costs; however, when integrated into a national model, it is no longer the cheaper option (Table 28). This occurs despite the fact that the same price data was specifically provided in the two economic analyses (the industry sector and the Greek energy system) to account for this. For example, an LCOE analysis of biomethane was done to compare the costs -as sourced from interview 8.1- and used in the cost analysis of the industrial sector and the ones already existing in the Greek energy model. The difference between them was insignificant. This example demonstrates the importance of integrating each energy sector into the energy system when planning a national energy strategy. Therefore, this study extracts conclusions from the results from the Greek energy model because they reflect the actual total costs for Greek society.

All other proposed 2050 scenarios for Greece's transition to renewable energy have zero CO_2 emissions. When compared to the 2015 scenario, they include a relatively high SCC, and their annual costs are approximately €5,4 billion more expensive as a result. It has to be mentioned that the 2050 energy model is in many ways different than 2015 energy model. For instance, the 2050 energy model includes a 14% increase in industrial production and a rise in passenger cars (sEEnergies project, 2023). The comparison between 2015 and 2050 prices is a way to discuss the economic feasibility of the future scenarios (see 2.2.1) by keeping the annual energy system costs in the same order of magnitude. To summarize the results:

- Scenario 1 with the highest electrification in the industry has the 3rd highest biomass consumption together with the highest annual costs.
- Scenario 2 which is based on biomass and zero electrification has similar biomass consumption to scenario 1 and the lowest overall annual costs.
- Scenario 3 with high electrification and exclusive biomass-derived gaseous fuel use has the highest biomass consumption and second higher annual costs.
- Scenario 4 which combines electrification, with dry biomass and biomass-derived gaseous fuel has the second lower biomass consumption and second lower annual costs.
- Scenario 5, which includes high electrification and hydrogen utilization has the lowest biomass consumption but higher costs than scenario 2 and scenario 4.

It is clear from these scenarios that electrification rises the overall cost because it requires a high amount of investment and alone cannot decrease biomass consumption. The extra electricity consumed in an electrified system has to be produced by VRES. Otherwise, rising EE increases the biomass combusted for electricity production.

Considering the previous paragraphs, scenario 4 is cheaper than scenario 5 because it has lower investment costs and utilizes some biomass which is a cheaper fuel than biomethane. Another benefit of scenario 4 is that it focuses on the consumption of gases that are identical to natural gas and industries do not have the difficulties of handling H_2. Part of the industry uses biomass, and the other part uses biomethane. This scenario offers more flexibility (diversification of fuels) and does not require industries to invest in hydrogen (production, storage, equipment, combustion process).

Furthermore, sensitivity analysis confirms that the inclusion of gaseous electrofuels in the gas grid can significantly reduce biomass consumption with an extra cost of €140-150 million. Again, the available fuels for the industry will be biomass, biomethane and e-methane and there is no need for extra fuel substitution-related investments from the industries.

To sum up, scenario 4 is the preferable one. The additional cost of electrofuels in the natural gas distribution grid depends on the final biomass raw material that will be available in Greece in 2050. The next chapter aims to point out some measures which will contribute to the implementation of scenario 4.

6 Recommendations

The purpose of this chapter is to propose measures for overcoming the technical and economic barriers that the Greek industrial sector faces in its transition to renewable energy. This section draws on the above analysis, the interviews conducted with employees in the Greek industrial sector and the literature review.

One significant difficulty faced when conducting this project was the availability of reliable data regarding raw biomass potential. To proceed to strategic planning, there is a need for concrete data which is renewed on a continuous basis and their collection process is transparent and clear. Biomass will be a significant part of the future energy system as it has similar characteristics to fossil fuels and can be utilized when it is needed, in contrast to VRES. Therefore, it must be clear how much is available at a sustainable level. Greece has significant potential and can also contribute to other countries' goals and be a biomass net exporter. A resource with such potential should be prioritized on the governmental agenda.

The Greek government should prioritize the development of biomass production, transportation, and gasification in the next years. Emphasis should be given at the municipal level for proper waste collection and especially agricultural and forested municipalities to gather their agricultural residues. Farmers should be informed about the financial benefits of planting sequential crops between their ordinary production and wooden biomass. There is a need for an organization responsible for the collecting and processing of biomass and informing producers.

Also, EBA, (2020) states that the EU has to characterize sustainable biogas which derives from sequential crops and provide financial motives to produce it. Following this, the Greek legal framework and the technical regulations for biomass use, biomethane injection in existing natural gas grids, as well as biomass origin certification procedure shall be prepared.

Moreover, there has to be a database including the quantity and the temperature level of the heat consumption of each industry. The Greek government should legislate in order to require industries to be more transparent and share data. This way researchers can propose specific measures for replacing fossil fuels in the industry and plan possible energy interconnections between neighboring industries.

Economic motives should be given to industries to also make the investments feasible from a societal aspect feasible from a business perspective. It is important to ensure that the price of electricity will be cheap, so the industries disregard the remaining lifetime of facilities and proceed to electrification. For industries where this is not possible, they are going to use biomethane.

New industries especially should have a strategy for carbon neutrality and be designed with that perspective. In some years will use carbon-neutral fuels or electricity.

Lastly, there is a need for an extra analysis considering the employment effect of the different scenarios and the economic benefits from biogas by-products like fertilizers which can reach 40-70 €/ MWh. The same applies to the gasification process which is also produces by-products like fertilizers and biochar (Sikarwar et al., 2016).

7 Conclusion

The industrial energy system of Greece is based on fossil fuels. The operating costs in 2015 were high, and 33 Mt of CO_2 were emitted annually. The intended energy transition in the industrial sector faces many difficulties such as sunk investments, complicated industrial processes, and lack of knowledge. This study aims to raise awareness and show a feasible and economically viable way to achieve a fossil-free industrial fuel mix. More specifically, the research aims to answer the research question:

How can the Greek industry exploit sustainable biomass and feasible substitute fossil fuels by 2050?

A feasibility study has been done to answer the RQ. This study is divided into 4 sections.

The first section is about specifying raw biomass potential. This part of the analysis shows that Greece has significant potential for the production of biomethane and dry biomass.

The second section is about identifying the future industrial demand. This analysis presents two strategies to identify the fuel mix. One is based on interviews and literature review and the second is based on the tool IndustryPLAN. After this analysis, five future fossil fuel-free scenarios are specified, all with different levels of electrification, use of biomethane, dry biomass or H_2.

In the third section, these scenarios are integrated into the Greek energy model in EnergyPLAN, and the analysis shows how it is affected technically by the changes in the industry sector. In this section, the main factor assessment is biomass consumption which is approximately 4,3 to 6,4 TWh higher than the potential specified in the first part of the analysis but lower than the sustainable biomass future potential defined at the beginning of the study. A scenario regarding industry with utilization of H_2 and dry biomass has the lowest dry biomass consumption (scenario 5).

The fourth part evaluates the previous scenarios and includes a sensitivity analysis of how less biomass available affects the system technically and economically. Firstly, financial analysis investigates the scenarios in the industry abstracted from the rest of the energy model. This analysis concludes that a high electrification scenario utilizing H_2, and dry biomass is the most sufficient moneywise (scenario 5). The economic analysis follows, which includes the whole Greek energy model. This analysis demonstrates that a no-electrification scenario which also uses large quantities of dry biomass and lower quantities of biomass-derived gaseous fuels is the cheapest (scenario 2). The results of these two analyses differ because each change in the industry's energy system affects the rest of the country's energy system. These changes are not visible in an economic analysis focusing only on the industrial sector. The sensitivity analysis shows that even for the scenarios with the highest biomass consumption, it is possible to reduce it by utilizing e-fuels with an added cost of 140-150 million €.

The chosen scenario is the one with high electrification and higher use of biomass-derived gaseous fuels (scenario 4) as it is the second cheapest, consumes less biomass than the cheaper scenario and offers the greatest fuel flexibility. The exact amount of electricity, dry biomass and gaseous fuel will depend on the real biomass available in 2050.

In conclusion, Greece can achieve zero CO_2 emissions in the industry and at a national level at the same time. It can be energy secure, as all the energy needed is produced inside the country and does not exceed sustainable biomass potential. Any additional biomass resources that might occur can be exported with further economic benefits. According to the sEEnergies project, (2023), many European countries lack the biomass resources they need and Greece may be able to contribute also to EE energy security and decarbonization.

8 Appendices

8.1 Interview with a member of the BlueGrid company

Interviewer (A): Ioannis Skarpetis Tsamopoulos

Interviewee (B): Odisseas Rigopoulos (Head of renewable fuels division)

Odisseas is an engineer specializing in renewable fuels. He shared documents which include data regarding biomethane potential in Europe (Alberichi et al., 2022; European Biogas Association, 2022) and the European directive (Renewable Energy Directive, 2018) which drives the market trends. He offered indicative prices of raw material for a biomass plant of 60.000 tn/y costs 600.000 (including transportation costs).

Table 32, Table 33, and Table 34 summarize the cost-related information he shared.

	1MWel./2,5MWth. Option - ~20.000MWth. Production				
		Biogas for Electricity	Biogas as a Step for Biomethane	Biomethane	BioLNG
CAPEX	Digester (M€)	3,8	3,8		
	CHP (M€)	0,7			
	Upgrade (M€)			1,2	
	Liquefaction (M€)				N/A
O&M (M€)	Feedstock (k€)	600	600		
	Power Consumption (k€)	95	78	140	N/A
	Maintenance (k€)	80	30	50	
	Other Consumables (k€)			15	
	Personnel	80	80	No extra personnel needed	
	Other OPEX (k€)	55	55	65	

Table 32: CAPEX and OPEX of a 1 MW biogas

	3MWel./7,5MWth. Option - ~60.000MWth. Production				
		Biogas for Electricity	Biogas as a Step for Biomethane	Biomethane	BioLNG
CAPEX	Digester (M€)	8,8	8,8		
	CHP (M€)	1,7			
	Upgrade (M€)			7,2	
	Liquefaction (M€)				
O&M (M€)	Feedstock (k€)	1800	1800		
	Power Consumption (k€)	285	235	870	
	Maintenance (k€)	240	90	215	
	Other Consumables (k€)			45	
	Personnel	120	120	No extra personnel needed	
	Other OPEX (k€)	90	90	60	

Table 33: CAPEX and OPEX of a 3 MW biogas

Biogas for electricity production	55-65 €/MWh
Biomethane	70-80 €/MWh
bioLNG	80-90 €/MWh

Table 34: Average production costs

8.2 Interview with employees in Greek industry

Interviewer: Ioannis Skarpetis Tsamopoulos

Iron & steel industry

Interviewee: Dimitris Kolaitis

Role in the company: Business Development Executive with a focus in the Energy Transition

Summary of the interview:

In Greece, this sector utilizes scrap which is melting in electric furnaces to produce billets. These billets are heated in 1100 °C in furnaces that use electricity or natural gas to be suitable for rolling. Already 70%-80% of the energy consumption is electricity and in 2050 the remaining gas consumption could be 5%. The only barrier to electrification could be much higher electricity prices than natural gas prices.

Glass industry

Interviewee: Theodore Zitounis

Role in the company: Technical manager at Yioula Glassworks (ex.)

Summary of the interview:

- 95% of the industrial processes is at a temperature level of 250<T<1000.
- 20 % of the non-electrified demand will be gaseous fuel.

Paper company

Interviewee: Alkis Zourbakis

Role in the company: Engineer in *Intertrade Hellas*, (2023).

Summary of the interview:

In this industry, 95% of the thermal processes need a temperature between 250 °C<T<1000 °C. Another 5% of the non-electrified energy demand is considered low-temperature heat, bellow 180 °C.

20 % of the non-electrified demand will be gaseous fuel.

Food company

Interviewee: **Georgios Christopoulos**

Role in the company: Technical manager at KOLIOS dairies

Summary of the interview:

- 40% low temperature
- 60% thermal processes are between 250<T<1000.

- 10% of the non-electrified demand will be gaseous fuel.

8.3 Data collection- Greek industries

Iron & steel industry

Process	% Energy	Temperature	Source
Blast furnace, including stoves and blowers	53 %	1500-1600	(Sun et al., 2022)
Coke oven	9%	1150-1350	(He & Wang, 2017)
Sinter plant	8%		
Hot rolling mill, including reheat furnace	7%		
Electric arc furnace	2,5 %		
Basic oxygen furnace	0,5 %		
Casting	0,4 %		
Boilers, power generation, finishing processes	20%		

Table 35: Iron & steel industry energy use (Griffin & Hammond, 2019)

Chemical industry

The percentages of the needed energy for each temperature are based on the British chemical industry (Griffin & Hammond, 2019).

Aluminium industry

Approximately 25% of the direct energy consumption used in that industry is used for alumina production and 65% for aluminium electrolysis (Peng et al., 2019). The first process is at a temperature of 1000 and the second of (950-1000) which is mostly electricity (Brough & Jouhara, 2020). The assumption is that 70% of the non-electrified energy demand is covered by green gases and the rest is electrified.

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