# LIFE CYCLE ASSESSMENT OF ENERGY AND VALUE-ADDED PRODUCT GENERATION FROM BIOMASS BY PYROLYSIS

by

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# LIFE CYCLE ASSESSMENT OF ENERGY AND VALUE-ADDED PRODUCT GENERATION FROM BIOMASS BY PYROLYSIS

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Dedicated to my lovely grandparents Latife Sağlam & Halis Sağlam

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# ABSTRACT

## LIFE CYCLE ASSESSMENT OF ENERGY AND VALUE-ADDED PRODUCT GENERATION FROM BIOMASS BY PYROLYSIS

The sustainable management of biomass waste from food and raw materials is a critical issue today. Meanwhile, global energy demand is constantly increasing with the rapidly growing population and industrialization. Today, most of the energy used is still fossil fuels, and this dominance is a significant obstacle to the sustainable energy transition. The European Green Deal aims to make a sustainable economy possible by drawing attention to the transformation of climate and environmental problems brought about by these problems. At this point, pyrolysis technology offers a promising solution. It provides a cleaner way of waste management by providing valuable chemicals from biomass waste and energy generation. It enables us to use resources efficiently in line with the principles of circular economy.

In this study, the environmental performance of a biomass waste pyrolysis plant, which obtains energy and valuable products by pyrolysis of biomass waste, was evaluated using the life cycle assessment methodology, and scenarios in which energy is assessed in different ways were discussed. In addition, changes in environmental impacts of this clean production plant, which contributes to the circular bioeconomy, were examined in the changing 2030 and 2053 electricity projections. The results show that environmental impacts are mainly due to the electricity consumption used in the production processes throughout the life cycle and the exhaust emissions of the cogeneration unit, and the system has the potential to make a positive contribution to abiotic depletion potential by producing activated carbon from biochar and converting biomass into energy.

# ÖZET

## BİYOKÜTLE ATIKLARININ PİROLİZİNDEN ENERJİ VE DEĞERLİ ÜRÜNLER ELDESİNİN YAŞAM DÖNGÜSÜ ANALİZİ

Gıda ve hammaddeden kaynaklanan biyokütle atıklarının sürdürülebilir yönetimi kritik bir konu olarak karşımıza çıkmaktadır. Öte yandan, küresel enerji talebi, hızla artan nüfus ve endüstriyelleşme ile birlikte sürekli bir artış göstermektedir. Günümüzde kullanılan enerjinin çoğunluğunu ise hala fosil yakıtlar oluşturmaktadır ve bu hakimiyet sürdürülebilir enerji geçişinin önünde önemli bir engel teşkil etmektedir. Avrupa Yeşil Mutabakatı, bu problemlerin beraberinde getirdiği iklim ve çevre sorunlarının dönüştürülmesine dikkat çekerek sürdürülebilir bir ekonomiyi mümkün kılmayı amaçlamaktadır. Bu noktada umut vadedici bir çözüm sunan piroliz teknolojisi, biyokütle atıklarından değerli kimyasallar eldesi sağlamasının yanı sıra enerji eldesine olanak sağlaması ile atık yönetiminin daha temiz bir yolunu sunmakla kalmayıp aynı zamanda döngüsel ekonomi ilkeleriyle de uyumlu bir şekilde kaynakları verimli kullanmamızı sağlamaktadır.

Bu çalışmada biyokütle atıklarının pirolizi ile enerji ve değerli ürünler elde eden bir biyokütle atığı piroliz tesisinin çevresel performansı yaşam döngüsü değerlendirmesi metodolojisi kullanılarak değerlendirilmiş ve enerjinin farklı şekillerde değerlendirildiği senaryolar ele alınmıştır. Ayrıca, döngüsel biyoekonomiye katkı sağlayan bu temiz üretim tesisinin değişen 2030 ve 2053 elektrik projeksiyonlarında çevresel etkilerindeki değişim incelenmiştir. Sonuçlar göstermektedir ki çevresel etkiler büyük oranda yaşam döngüsü boyunca üretim süreçlerinde kullanılan elektrik tüketiminden ve kojenerasyon ünitesinin egzoz emisyonlarından kaynaklanmaktadır ve biyokömürden aktif karbon üretimi ve biyokütleyi enerjiye dönüştürmesi ile sistem ADP'ye olumlu katkı sunma potansiyeline sahiptir.

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# LIST OF SYMBOLS/ABBREVIATIONS

| **Symbol** | **Explanation** |
|---|---|
| $CH_4$ | Methane |
| CO | Carbon monoxide |
| $CO_2$ | Carbon dioxide |
| GJ | Gigajoule |
| $H_2$ | Hydrogen |
| kWh | Kilowatt-hour |
| MJ | Megajoule |
| $NO_x$ | Nitrogen oxides |
| $SO_2$ | Sulphur dioxide |
| **Abbreviations** | **Explanation** |
| ADP | Abiotic Depletion Potential |
| EP | Eutrophication Potential |
| EU | European Union |
| GHG | Greenhouse Gas |
| GWP | Global Warming Potential |
| HTP | Human Toxicity Potential |
| ISO | International Organization for Standardization |
| LCA | Life Cycle Assessment |
| LCI | Life Cycle Inventory |
| LCIA | Life Cycle Impact Assessment |
| MEA | Monoethanolamine |
| MEATP | Marine Aquatic Ecotoxicity Potential |
| RPM | Revolutions per minute |
| SDG | Sustainable Development Goals |
| TUIK | Türkiye İstatistik Kurumu |
| UN | United Nations |
| WWTP | Wastewater Treatment Plant |

# 1. INTRODUCTION

Globalization, rapid population growth, and industrialization have increased the demand for energy resources day by day. Although the share of renewable energy sources in energy consumption has increased today, these sources are still limited in total energy consumption, and fossil fuels still provide the majority of energy. Using these fuels causes severe environmental damage and the release of greenhouse gases that cause climate change, increase global warming and disrupt the environmental balance (Noszczyk et al., 2021).

The dominance of fossil fuels in meeting energy needs poses a significant obstacle to sustainable energy transition. The European Green Deal aims to enable a sustainable economy by drawing attention to transforming the climate and environmental challenges brought about by this dominance. In this regard, the European Union encourages short-term goals to increase the share of renewable energy sources to at least 42.5% and increase energy efficiency by 2030, in line with the 2050 carbon-neutral target (European Commission, 2023). Therefore, promoting effective policies and technological advances to reduce dependence on fossil fuels and broader adoption of renewable energy sources to meet the European Union targets are critical to meeting increasing energy demands and reducing environmental concerns.

While climate change threatens the world and the human population grows exponentially, in addition to the environmental burdens caused by energy consumption-related problems, problems arising from increasing waste production also emerge as another critical problem (Ferdoush et al., 2024). In particular, how to sustainably manage the inevitable biomass waste produced from providing food, energy, and water to human society, directly or indirectly, emerges as an essential issue. Proper management of this inevitable biomass waste becomes one of the critical factors in achieving a sustainable future. Traditional ways to manage such waste include composting, fertilizing, feeding, and landfilling. However, because they cause uncontrolled greenhouse gas emissions, surface water, groundwater pollution, and pathogen spread, these traditional methods become unsustainable options and, over time, cause severe environmental damage and energy and material loss. Modern sustainable waste management technologies involve the conversion of waste into energy, fuels, and valuable products for the systematic use of biomass resources; this is also considered a cleaner way of managing biomass and organic waste (Wang & Tester, 2023).

Among these technologies, the pyrolysis of biomass waste has emerged as a promising solution for sustainable waste management. Pyrolysis not only mitigates environmental impacts but also supports the transition to renewable energy and contributes to achieving climate neutrality targets,

This study aims to determine environmental hot spots with a door-to-door life cycle analysis study of a facility that produces energy and active carbon as main products and pyrolytic oil and carbon dioxide as by-products of pyrolysis of hazelnut shells in the Black Sea Region of Turkey. The current widespread disposal methods of these wastes, which have an important biomass potential for Turkey, are also discussed within the scope of this study. In this way, while increasing the share of renewable energy in energy production in Turkey, the effectiveness of establishing a facility that offers circular economy modeling by producing valuable products in terms of environmental impacts and benefits of biomass is examined compared to the current management in Turkey.

# 2. LITERATURE REVIEW

## 2.1. Life Cycle Assessment Concept

Life Cycle Assessment (LCA) is a beneficial tool to evaluate the environmental impact of a process, activity, or product throughout its entire life cycle. It comprehensively analyzes the environmental aspects and potential impacts, including resource use, energy consumption, global warming potential, acidification, and waste generation (Kikuchi & Kanematsu, 2020).

The idea of LCA originated in the 1960s when environmental degradation and especially limited access to resources became a cause for concern. It became popular in the 1990s when companies started focusing on environmental impacts and the need for a standardized method to assess them (Bjørn et al., 2017). The early adoption of LCA was driven by the need for environmental impact assessment and management, particularly in the European Union, where policies and regulations were introduced to reduce the environmental impact of products and processes. Since then, LCA has been widely adopted by companies in various industries to evaluate the environmental impact of products and processes, from raw material extraction to disposal (Sala et al., 2021).

Some guidelines have been published by the International Organization for Standardization (ISO) to ensure standardization and its international acceptance in the conduct of LCA studies. The series, called ISO 14040, consists of the following standards (International Organization for Standardization, 2006a).

1. ISO 14040: Environmental management - Life cycle assessment - Principles and framework: This standard lays out the fundamental principles and framework for conducting an LCA. It defines the goal and scope of the assessment, outlines the life cycle stages to be considered, and provides guidance on inventory analysis, impact assessment, and interpretation of results.

2. ISO 14044: Environmental management - Life cycle assessment - Requirements and guidelines: This standard complements ISO 14040 by specifying the detailed requirements and guidelines for conducting an LCA. It guides data quality, data collection and analysis, choice of impact assessment methods, and reporting of results. ISO 14044 emphasizes the importance of transparency, consistency, and sensitivity analysis in LCA studies.

### 2.1.1. Application of Life Cycle Assessment

LCA assist in (1) identifying opportunities to improve the environmental performance of products at specific points in their life cycle, (2) inform decision-makers such as government and non-governmental organizations, (3) the choice of relevant metrics to measure environmental performance, (4) marketing to make an environmental claim or prepare an environmental product statement (International Organization for Standardization, 2006a).

According to the ISO 14040 series of standards, there are four stages in an LCA study, and all these stages are in relationship with each other as Figure 2.1 (International Organization for Standardization, 2006a):

a) the goal and scope definition phase aims to define the intended application, reasons for conducting the study, and provide a clear framework for conducting comprehensive environmental analyses.

b) the inventory analysis phase defines the energy and material flows within the evaluated system and their interaction with the environment.

c) the impact assessment phase aims to evaluate the potential environmental impacts associated with a product or system using inventory data collected in the previous phase.

d) the interpretation phase involves analyzing and deriving actionable insights from the results of the LCA to inform decision-making and identify opportunities for environmental improvement.

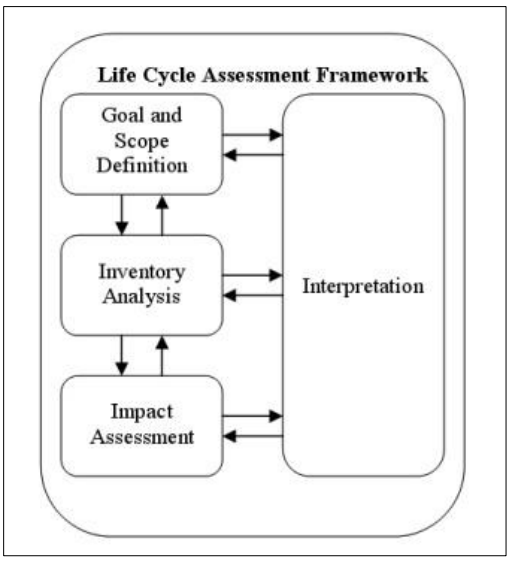


Figure 2.1. Phase of an LCA.

### 2.1.2. LCA Software

There are many software tools developed for LCA studies to calculate the environmental impacts of a product or process. LCA studies are designed for applications in different fields, and the main current LCA software tools are SimaPro, GaBi, Umberto and openLCA. GaBi is one of the most used software tools in the literature and market as commercial LCA tools. GaBi software provides a comprehensive platform to conduct LCA studies and evaluate the environmental impacts of products, processes and systems (Lopes Silva et al., 2019).

## 2.2. Pyrolysis

Pyrolysis is a thermochemical process that involves the decomposition of organic matters in the absence of oxygen and at high temperatures. With the pyrolysis process, energy-rich products are obtained by heating and holding the biomass in the absence of oxygen. The main products are generally syngas ($CO_2$, $CH_4$, CO, $H_2$), tar, and bio char (Karaca et al., 2018). Pyrolysis process parameters can significantly affect pyrolysis products' quality, yield, and physicochemical properties. Since the process parameters are crucial in determining and improving the final quality and quantity of the output, the pyrolysis process can be modified to increase the yield of pyrolytic products (Al-Rumaihi et al., 2022).

Pyrolysis reactors vary in heat transfer mechanisms, reaction time, operating temperature, feedstock feeding rate, product yield, and scalability. Different reactor types are chosen to ensure more efficient conversion based on the feedstock's various physical and chemical properties. Auger-type pyrolysis reactors are particularly interesting due to their versatility in converting a wide range of feedstocks(Campuzano et al., 2019). They are preferred for biomass or waste pyrolysis as they provide better performance in heat transfer for these feedstocks. Figure *2.2* presents a general view of an auger-type pyrolysis reactor.

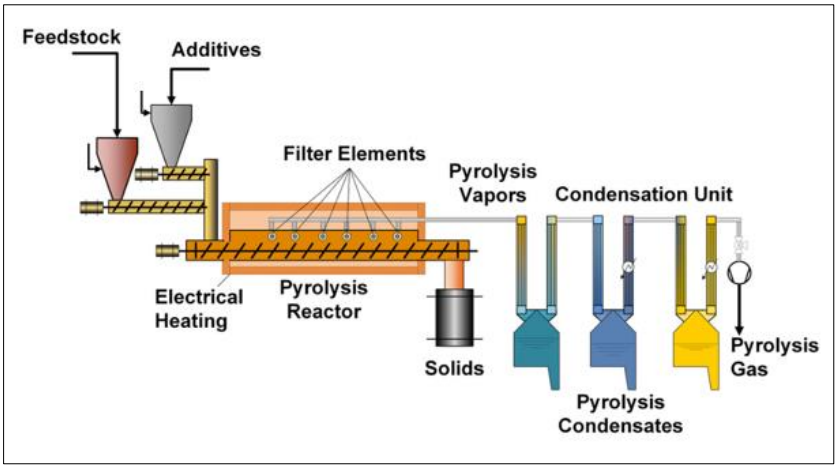


Figure 2.2. General View of Auger (Screw) Type of Pyrolysis Reactor (Karlsruhe Institute of Technology, n.d.).

### 2.2.1. Biomass Pyrolysis

Pyrolysis is one of the thermochemical technologies used to convert biomass into energy, synthesis gas, hydrogen-rich gases, and chemical products consisting of liquid bio-oil, solid biochar, and pyrolytic gas (Kan et al., 2016).

In recent years, biomass pyrolysis has received more and more attention as a thermochemical conversion process to obtain value-added products. It is also possible to maximize the production of high-quality hydrogen through the development of state-of-the-art technology and innovative processes (Vuppaladadiyam et al., 2022).

Biomass pyrolysis is generally carried out by a three-step mechanism of dehydration, primary and secondary reactions. Dehydrogenation, depolymerization, and degradation are the main competitive reactions in the primary decomposition of biomass. Biomass type, type of biomass pretreatment (physical, chemical, and biological), reaction atmosphere, temperature, heating rate, and steam residence time affect the biomass pyrolysis process, yields, and properties of products (Kan et al., 2016).

Pyrolysis is one of the most widely used methods of obtaining renewable energy from biomass, as well as the first stage of many thermal processes. Various types of lignocellulosic or contaminated biomass can be used as feedstock to produce bio-oil, biochar, and pyrolytic gases during the pyrolytic process (Poskart et al., 2021).

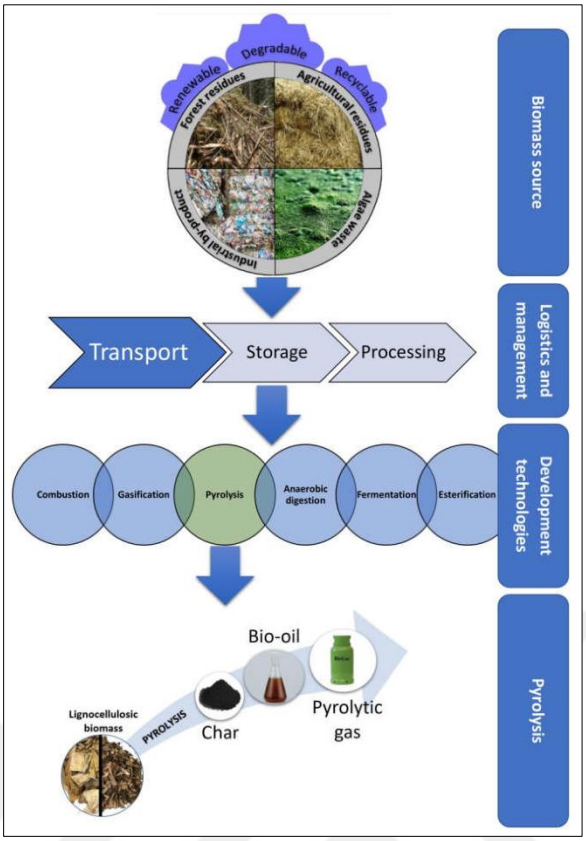


Figure 2.3. Scheme of Biomass Waste Treatment and Pyrolysis Products (Poskart et al., 2021).

Biomass pyrolysis is generally divided into three main types, slow, fast, and flash pyrolysis, depending on the residence time and temperature of the process. However, no sharp boundaries separate these industrial classifications (Fahmy et al., 2020):

**a) Slow Pyrolysis**

Slow pyrolysis is carried out over a relatively long period, reaching several days. It is usually carried out at relatively low temperatures not exceeding 500 °C and slow heating rates of 0.1 to 2 °C per second. The main products of slow pyrolysis are coal and tar because the residence time of gases and other pyrolysis products enables repolymerization/recombination reactions to take place (Fahmy et al., 2018). New industrial examples of slow pyrolysis focus on biochar production while using the produced bio-oil and biogas as an energy source for pyrolysis. In addition, valuable chemicals such as acetone, methanol, and acetic acid can be collected from slow pyrolysis (Kan et al., 2016).

**b) Fast Pyrolysis**

Fast pyrolysis is carried out in the high-temperature range of 300–700°C, at a faster heating rate of 10–200°C/s, with a short solids resistance time of 0.5–10 s. The main products in rapid pyrolysis are liquid and gas phase products (Fahmy et al., 2020). The main products of fast pyrolysis are bio-

oil and gaseous products. Fast pyrolysis is recognized as a direct thermochemical technique that can liquefy solid biomass into liquid bio-oil with high energy application potential.

**c) Flash Pyrolysis**

Fast heating rates can reach up to 2500 °C per second in flash pyrolysis. The entire process can be completed in 0.1 to 0.5 seconds. Medium temperatures ranging from 400 to 600 °C can reach 1000 °C, which can characterize sudden pyrolysis. The main ingredient in flash pyrolysis products is the liquid phase, bio-oil (Fahmy et al., 2020).

### 2.2.2. Value-Added Pyrolysis Products and Their Applications

*2.2.2.1.* Syngas. One of the valuable products formed as a result of biomass pyrolysis is synthesis gas (also known as syngas). Synthesis gas is a fuel gas consisting mainly of H2, CO, and CH4, with a low amount of CO2 depending on the raw input material and production method. While synthesis gas can be used directly in energy production, it is also a critical intermediate source for producing ammonia, hydrogen, methanol, or synthetic hydrocarbons (Ahmed El-Nagar & Ghanem, 2019).

Synthesis gas can be used in many different industries due to its versatility as a fuel. It is also increasingly important as a cleaner and more efficient way to produce electricity, as it reduces the need for fossil fuels and creates far fewer greenhouse gas emissions and pollutants. In addition, synthesis gas, a carbon energy source, can be converted into chemicals and fuels by synthesis gas fermentation (Ahmed El-Nagar & Ghanem, 2019). The most frequently produced byproducts of this process are ethanol, butanol, acetic acid, butyric acid, and methane. One of the areas where synthesis gas is used most is the chemical industry. Synthesis gas can be used as the basis for producing various chemicals and diesel fuels thanks to the Fischer-Tropsch synthesis process (Mackaluso, 2007). Synthesis gas usage areas are summarized in Figure 2.4.

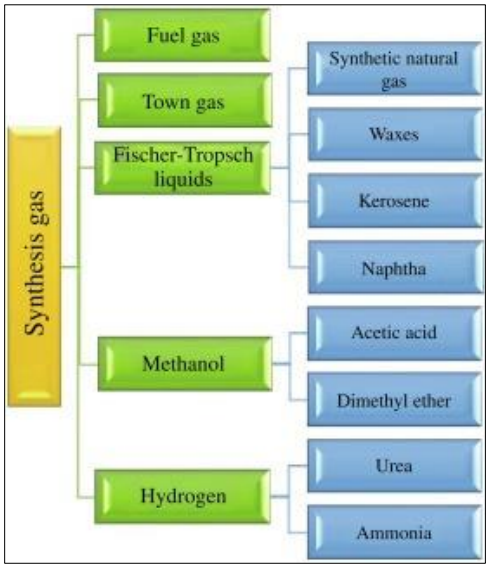


Figure 2.4. Syngas Applications (Ahmed El-Nagar & Ghanem, 2019).

The capture and purification of $CO_2$ and $H_2$ and its use for product synthesis and upgrading are trending topics in future application paths of syngas. Gases in syngas can be optimized with reforming technologies and catalyst systems. In addition, carbon capture technologies enable carbon-neutral energy production processes by separating $CO_2$ from syngas. Electrocatalytic and photocatalytic upgrade methods have low energy consumption and environmental sustainability advantages. Similarly, plasma technologies offer the potential to convert syngas into methanol and hydrocarbons quickly and efficiently. Pyrolysis gas supports sustainable resource use by increasing energy use efficiency and economic value, reduces dependence on fossil fuels, and contributes to protecting the environment and ecosystems. However, the development of related technologies and the innovation of industrial processes can increase the competitiveness of enterprises and stimulate the growth of the pyrolysis gas industry. Pyrolysis gas has excellent development potential in maximizing the yield of target products through catalytic co-pyrolysis and producing value-added products through gas purification and capture processes (Zhang et al., 2023).

Various methods can be used to convert the synthesis gas obtained from pyrolysis into electrical energy. Cogeneration systems are a method that can contribute to environmental sustainability by providing high energy efficiency by producing both electricity and heat from the same fuel source and by lowering carbon emissions compared to other electricity generation methods. As seen in Figure 2.4, cogeneration systems operate an electric generator by compressing air and burning gas or liquid fuels. High-temperature exhaust gases from gas turbines are also used in the waste heat boiler to obtain high-efficiency heat energy. These systems, which allow the heat released from combustion to be recovered as heat energy instead of being discharged from the exhaust, significantly increase

energy efficiency (Rahim & Gündüz, 2013). The electrical energy obtained can be directly fed to the electrical grid. The heat energy obtained can be used for various heating purposes, such as space heating and domestic hot water production (Dincer İbrahim & Erdemir Dogan, 2021).

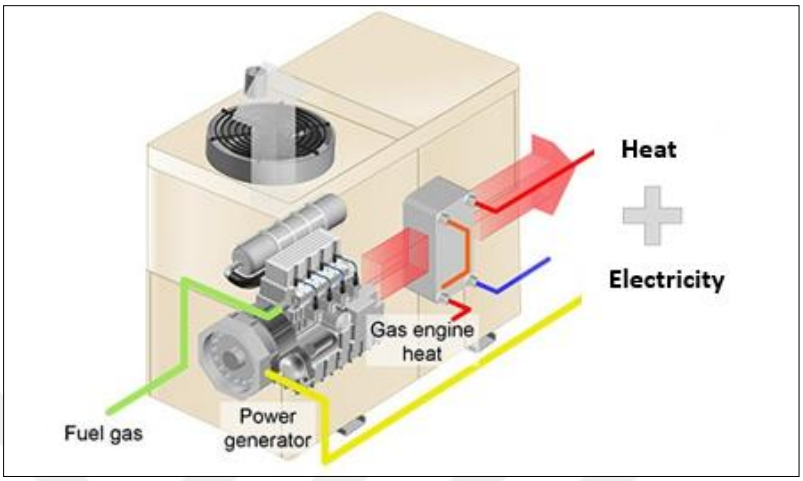


Figure 2.5. General View of the Cogeneration System (Yanmar, n.d.).

*2.2.2.2.* Activated carbon. Another valuable product obtained from biochar formed as a result of the pyrolysis of biomass waste is activated carbon. Activated carbon is carbonaceous adsorbent synthesized physically or chemically from carbonaceous materials with high carbon content, significant volatile substances, and low ash content. Activated carbon is a widely used product with applications in a wide variety of sectors. It has a sustained growth rate of over 10% worldwide and a multi-billion-dollar annual market with widespread use across many major industries (Tibor & Grande, 2022). Some examples of various uses of activated carbon are shown in Figure 2.6:




Figure 2.6. Activated Carbon Applications (Reza et al., 2020).

Non-renewable resources such as coal, peat, lignite, bone coal, and petroleum coke were commonly used in activated carbon production. With the increased environmental awareness, activated carbon production has been reshaped by introducing the concept that daily waste materials such as biomass waste, old tires, and plastics are also potential sources of activated carbon production (Saleem et al., 2019). Such sustainable production practices, which include the conversion of biochar produced by pyrolysis from bio-waste into activated carbon, have essential benefits such as waste management and resource conversion by contributing to the bioeconomy (Tibor & Grande, 2022). These applications provide environmental and economic benefits by ensuring the economical use of waste materials and reducing their environmental impact.

Different activation methods and reactor types can be used to obtain activated carbon from biochar released after pyrolysis. While physical activation can be carried out at high temperatures with gases such as water vapor, nitrogen, or carbon dioxide, chemical activation is carried out by treatment with various chemical reactants. Different reactor types are preferred to optimize the process's efficiency and the final product's properties.

In cases where nitrogen is used in physical activation, obtaining nitrogen from air is a preferred method. PSA-type nitrogen generators can be used for this process. This type of nitrogen generator uses the principles of pressure change and adsorption to produce nitrogen gas from atmospheric air. The process takes place in adsorption columns filled with special adsorbent material. While the adsorbent holds the nitrogen gas in the air, oxygen passes through it. As a result of the pressure change, nitrogen gas is released, taken from the generator, and stored for use. This cyclic process is repeated between multiple adsorption columns, thus continuously producing nitrogen gas (Marcinek et al., 2020). The carbonization process can be carried out in many different reactors, such as fixed bed reactors, rotary kiln reactors, and fluidized bed reactors. Rotary kiln reactors are one of the most preferred reactors in this process due to their homogeneous heat distribution. The general view of the operation of these furnaces with a long cylindrical structure is as in Figure *2.7*.

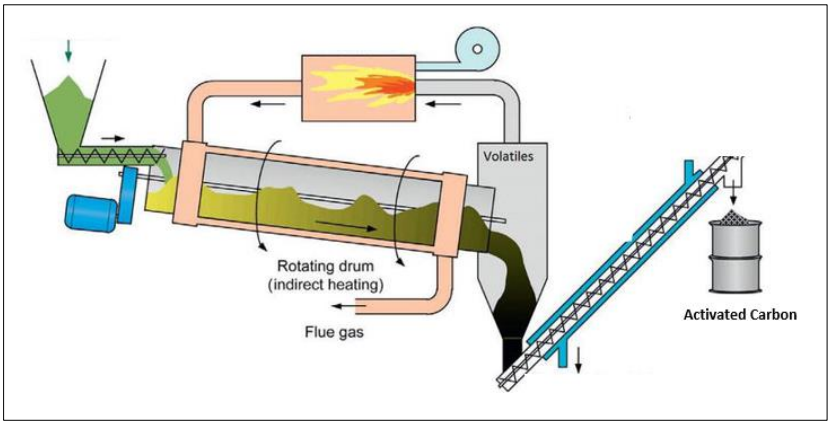


Figure 2.7. General View of Activation Process in a Rotary Kiln Reactor (Ronsse et al., 2015).

The biochar and physical activation agent to be carbonized is fed into this furnace. As the materials move along a rotating cylinder, they are heated by the heat source inside the furnace. This heat provides high temperatures at which the materials enter the carbonization process. After the active carbon extraction process, the obtained activated carbon is removed from the other end of the furnace (Mungyeko Bisulandu & Huchet, 2023).

*2.2.2.3.* Pyrolytic oil. Pyrolytic oil (also known as bio-oil), which can be obtained as a result of biomass pyrolysis, is a dark-colored, dense liquid that is formed as a result of the decomposition of organic materials at high temperatures and is an essential alternative in terms of energy efficiency and environmental sustainability (Hu & Gholizadeh, 2020).

Bio-oil is considered a renewable feedstock for producing chemicals, energy, carbon materials, and fuel. It can be converted into various valuable products in many ways, such as producing boiler fuel by direct combustion, biofuel through hydrotreating, and value-added chemicals through separation and acid catalysis/hydrogenation (Rasul et al., 2012). Some of the valuable products and methods that can be obtained from pyrolytic oil are shown in Figure 2.8:

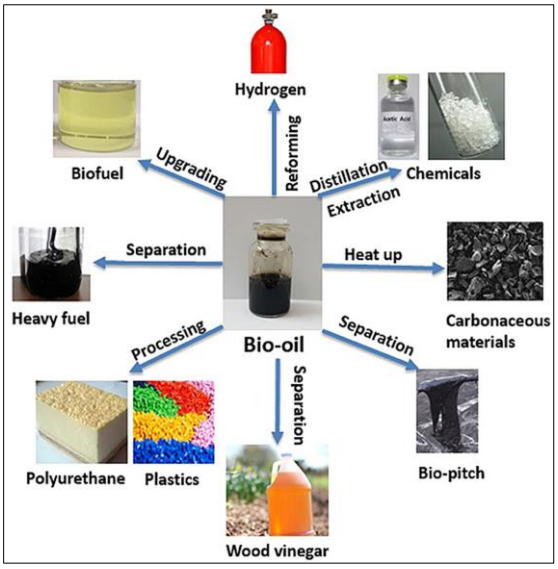


Figure 2.8. Bio-oil Applications (Hu & Gholizadeh, 2020).

### 2.2.3. LCA Application in Biomass Pyrolysis

Net carbon management of biomass waste is becoming an increasingly important option to reduce environmental burdens in agricultural production. The conversion of biomass waste into energy and valuable products by pyrolysis is a prominent method to achieve carbon neutrality in a circular economy that aims to reduce environmental burdens (Zhu et al., 2022). Life cycle assessment methodology is used to observe the actual environmental effects of this thermochemical transformation, which is carried out to obtain energy and valuable products from biomass wastes and to ensure sustainable waste management (Yu et al., 2022).

Conducting a life cycle assessment for pyrolysis technologies allows for understanding their sustainability in terms of environment and energy. LCA allows comprehensive analysis of the pyrolysis process for many environmental factors and its suitability for sustainable resource use. Furthermore, products of the pyrolysis process are assessed for energy efficiency and greenhouse gas emissions, exposing their environmental effects compared to fossil fuels. LCA evaluates not only the pyrolysis process but also the usage stages and final disposal of the products obtained so that the environmental benefits and potential damages after the process are determined. These assessments provide a scientific basis for creating low-carbon strategies and sustainable energy policies and show whether pyrolysis is compatible with these goals. It also allows for comparing pyrolysis plants operating with different energy sources or feedstock types to determine which scenario is more advantageous regarding the environment. LCA identifies the weak points of the process and reveals areas for improvement that will reduce energy consumption and emissions with innovative catalysts.

As a result, LCA helps maximize economic and environmental benefits by establishing the environmental sustainability of pyrolysis technology on a scientific basis. It is also an essential tool for achieving carbon-neutral energy production and circular economy goals (Gahane et al., 2022).

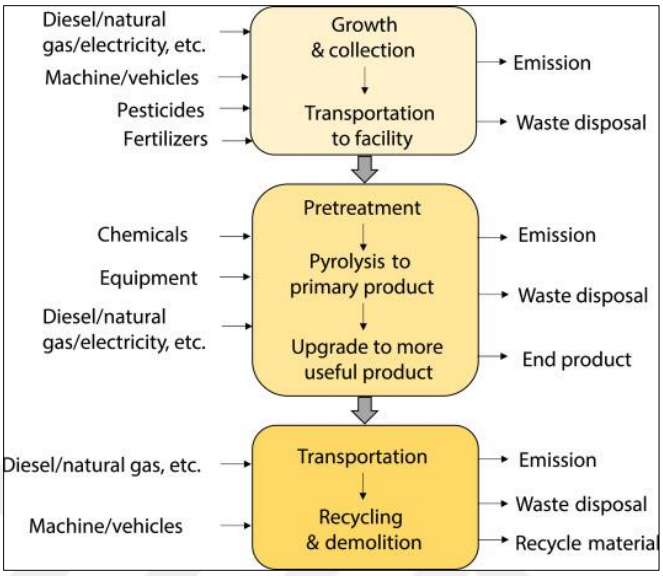


Figure 2.9. General System Boundary for LCA of Biomass Pyrolysis (Yu et al., 2022).

Choosing the appropriate functional unit in the definition of goal and scope is an important issue. The functional unit aims to provide a reference from which input and output data are normalized. Therefore, the functional unit must be clearly defined and measurable (International Organization for Standardization, 2006b). The standardized basis for calculation and reference, known as the functional unit, enables comparisons across different scenarios. The functional unit selection relies on the final product and the system's scope definition. In the life cycle assessment studies of biomass pyrolysis, common functional units are categorized as energy-based (such as 1 MJ, 1 kWh, or 1 MW of the end product) and mass-based (such as 1 kg or 1 ton of feedstock or product) (Han et al., 2013; Moreira et al., 2017; Zhu et al., 2022). Regarding energy products, a commonly used functional unit is the "unit of delivered energy," such as MJ. This functional unit is transparent and reliable when comparing alternative fuels with similar properties used in applications with comparable end-use efficiencies, for example, comparing petroleum gasoline and pyrolysis gasoline in internal combustion engine vehicles. By using the energy functional unit, complications arising from differences in end-use efficiencies can be avoided. On the other hand, for biofuels, a meaningful functional unit could be the "unit of biomass input," such as a tonne of dry biomass. This functional unit is particularly relevant because factors like land availability and biomass yield constrain the rate of biomass input. Therefore, when comparing different fuel production technologies, using the unit

of biomass input provides insight into the potential displacement of conventional fuels using a fixed amount of biomass resource or land (Han et al., 2013).

The selection of appropriate methods to allocate the environmental burden within a production system between products and co-products is a complex life cycle assessment (LCA) issue. Several methods have been proposed in the literature to address the ways of allocation. The choice depends on various factors and can include no allocation, economic allocation, biophysical allocation (such as energy or mass-based), attributional approach, or system expansion, depending on the specific context and goals of the assessment (Schrijvers et al., 2016). No allocation, where the entire environmental burden is attributed to the main product within the production system. Economic allocation allocates the environmental impacts based on the economic value of each product. Biophysical allocation allocates the environmental impacts based on physicochemical properties such as mass and energy content of the co-products and outputs. Some researchers argue that energy allocation is more accurate, reflecting economic considerations since the energy content determines the market value. Mass allocation, on the other hand, provides more stability over time compared to economic allocation, which price fluctuations can influence. The attributional approach addresses co-product allocation by partitioning the environmental impact of the main product using allocation factors based on mass, energy, or economic value. Lastly, system expansion is a method that evaluates the environmental impact of co-products by considering the avoided emissions from total emissions when the co-products are displaced. System expansion is particularly relevant when using the consequential approach to assess the environmental impact of co-products (Yu et al., 2022).

According to ISO 14044 methodology, the second step of an LCA study is life cycle inventory. Life cycle inventory (LCI) requires compiling data on inputs, outputs, and products within a system (International Organization for Standardization, 2006b). In the LCI of biomass pyrolysis energy and value products production systems, the quantities of inputs, direct emissions, and wastes at each stage are calculated based on a specific functional unit (Osman et al., 2021; Yu et al., 2022).

Life cycle impact assessment is the third step in an LCA study. This phase aims to understand and evaluate the magnitude and significance of possible environmental impacts for a product system (International Organization for Standardization, 2006b). When LCA studies for pyrolysis of biomass are examined, it is seen that the indicators chosen at this stage are generally global warming potential (GWP), acidification potential (AP), ecotoxicity potential (EP), eutrophication potential (ETP), water depletion potential (WDP) and fossil energy (FE) (Yu et al., 2022; Zhu et al., 2022). The studies that

integrated these indicators obtained results with human health, ecosystem quality, and resource consumption endpoint categories (Yu et al., 2022). Although different impact categories are included in the life cycle analysis studies of biomass pyrolysis, it is seen that global warming potential (GWP) is consistently chosen as the primary indicator.

The final stage of the LCA process is the interpretation of the results obtained. It is the phase in which the findings obtained from either or both of the inventory analysis or impact assessment phases are evaluated to reach conclusions and make recommendations in the life cycle assessment (International Organization for Standardization, 2006b). The interpretation results for the pyrolysis of biomass in the literature were examined within the scope of this study. Considering the net global warming potentials of biochar produced by pyrolysis, it is seen that the results vary between approximately (GWP) -440 and -1570 $CO_2$ eq/dry ton (Hammond et al., 2011; Ibarrola et al., 2012; Roberts et al., 2010). This wide GWP range may be due to differences in pyrolysis technologies, raw material selection, operational factors, and decisions regarding the limits and models used. When the articles interpreting the results of the LCA studies of biomass pyrolysis are examined, it is seen that another factor contributing to this variability is considered to be the handling of by-products (Yu et al., 2022; Zhu et al., 2022). For example, system expansion leads to changes in GWP values, taking into account credits for avoided products. For instance, when biochar is used as a fertilizer in system expansion, the GWP value differs, such as -1570 $CO_2$ eq/dry ton without system expansion, -1000 to -1200 $CO_2$ eq/dry ton, and -1250 $CO_2$ eq/dry ton with system expansion (Ibarrola et al., 2012; Yu et al., 2022).

A comprehensive review of life cycle assessment (LCA) studies on biomass pyrolysis highlights various systems, feedstocks, functional units, impact categories, and their respective LCA results. Yang et al. (2021) examined the utilization of crop residues for biochar implementation, with crop residues as feedstock, using 1 ton of crop residues as the functional unit. This study evaluated the global warming potential (GWP), acidification potential (AP), and eutrophication potential (EP), reporting a significant GWP reduction of -921.30 kg $CO_2$-eq per ton of crop residues. Arena et al. (2016) focused on producing activated carbon from coconut shells, with 1 ton of activated carbon as the functional unit. The impact categories assessed were GWP, human toxicity (HT), and AP, yielding results of 2.1 x $10^{-11}$ person equivalents for GWP, 1.2 x $10^{-10}$ person equivalents for HT, and 4.1 x $10^{-11}$ person equivalents for AP. Another study by Negro et al. (2017) investigated the pyrolysis of orange peel waste, using 1 ton of orange peel waste (wet weight) as the functional unit, and reported a GWP of 5.5 kg $CO_2$-eq. Lastly, Mo et al. (2022) explored biofuel production from the pyrolysis of

tropical agricultural waste, with 1 kg of biofuel as the functional unit. The study assessed GWP, HT, and AP, reporting a GWP of 0.988 kg $CO_2$-eq, an HT of 0.003 kg 1,4-DCB-eq, and an AP of 0.003 kg $SO_2$-eq. These studies demonstrate the diverse environmental impacts of different biomass pyrolysis processes.

It is to establish and increase the reliability and accuracy of the LCA and LCI study results, which includes identifying essential issues in the first element of interpretation in the evaluation of life cycle analysis results (International Organization for Standardization, 2006b). For this reason, sensitivity analysis is widely used to make LCA analysis more reasonable and realistic. Sensitivity analysis determines how different values of an independent variable affect the dependent variable under a given set of assumptions. The arguments in LCA can be parameter value, allocation rule, system boundary, model selection, or process selection (Yang et al., 2021).

### 2.3. Bioeconomy Perspective of Biomass Pyrolysis

Bioeconomy is an approach that encompasses knowledge, science, technology, and innovation related to the production, use, and conservation of biological resources. It aims to move towards a sustainable economy and provide information, products, processes, and services to all economic sectors (Food and Agriculture Organization of the United Nations, n.d.). This term became popular in the early 21st century when the EU adopted it to encourage the development of new products and markets with biotechnology. The EU then began implementing bioeconomy policies covering all sectors and systems dependent on biological resources (Popp et al., 2021). The EU emphasizes that sustainability and circularity must be at the heart of the bioeconomy to succeed in this goal. The EU states that this will happen through the renewal of industries with this approach and the modernization of primary production systems (European Commission, 2022).

Although bioeconomy is circular in nature, the concept of circular bioeconomy basically focuses on evaluating biological wastes and by-products within a circular economy. The European Commission defines the concept of circular bioeconomy as "reducing dependence on natural resources, transforming production, and promoting the sustainable production of renewable resources from land and marine biomass."(European Commission, 2013).

## 2.4. Hazelnut Shell Potential of Turkey

Turkey is the leader in world hazelnut production, accounting for approximately 70-75% of world production. Hazelnut production in Turkey is intensively carried out in the Black Sea Region; Ordu ranks first with 240 thousand tons, Samsun ranks second with 112 thousand tons, and Sakarya ranks third with 98 thousand tons. Turkey's total hazelnut production area is approximately 700,000 hectares, and annual production varies between 600-700 thousand tons (Aydemir, 2022 & Tarım ve Orman Bakanlığı, 2023). Hazelnut shells constitute 50% of hazelnuts by mass, produced in large quantities as a by-product of hazelnut processing processes in Turkey. Due to Turkey's leading position in world hazelnut production, more than 300 thousand tons of hazelnut shells are obtained yearly. Due to the limited alternative uses of hazelnut shells and their large storage volumes, they constantly accumulate as solid waste.

Thanks to their high calorific value, hazelnut shells are an important biomass source that can be used in energy production. Today, in Turkey, especially in the Black Sea Region, hazelnut shells are widely used for heating purposes in solid fuel stoves and boilers. Generally used in small combustion systems close to production areas and for domestic heating purposes, 10% to 20% of hazelnut shells are used as compost, animal feed, or organic fertilizer in agricultural areas. However, this usage rate remains quite low. Traditional disposal methods cannot fully utilize the potential of hazelnut shells as biomass and cause some problems in terms of environmental sustainability. Alternatively, energy, active carbon, and biofuel production from hazelnut shells through thermochemical conversion technologies offer opportunities to create higher economic value and reduce environmental impacts (Karakaş, 2017).

## 2.5. Turkey Electricity Mix Projections

Based on data announced by the Turkish Ministry of Energy and Natural Resources, 36.3% of Turkey's electricity production in 2023 will come from coal, 21.4% from natural gas, 19.6% from hydraulic energy, 10.4% from wind, 5.7% from solar, 3.4% from geothermal energy and 3.2% from other sources. (Ministry of Energy and Natural Resources of Turkey, 2024).

SHURA Energy Transformation Center has shared the energy plan detailing the past analyses and policies regarding Turkey’s electricity production and the projections for 2030 and 2053. In light of the data obtained from the Turkey National Energy Plan and SHURA report, the changes in electricity demand in 2030 and 2053 are estimated as in Figure *2.10*.

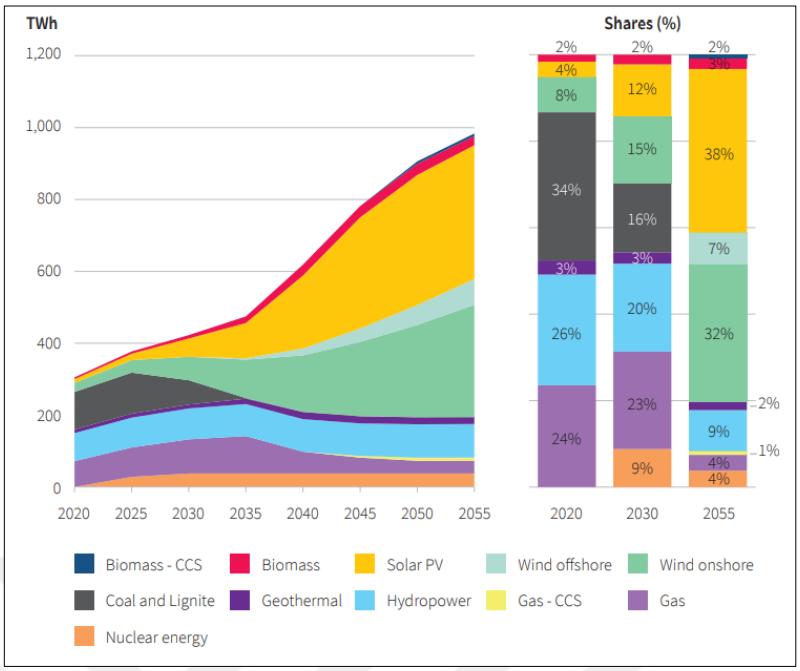


Figure 2.10. Turkey Electricity Generation Projections by Technology (SHURA Energy Transition Center, 2023)

When Turkey's electricity projections are examined, it is seen that solar energy stands out as an essential renewable energy source. A significant increase is predicted in the share of solar energy in 2030, and it is expected to become one of the primary sources in Turkey's energy mix by 2053. Wind energy is essential, especially in Turkey's regions with high wind potential, such as Western Anatolia, Marmara, and Central Anatolia. Terrestrial and offshore wind turbines stand out with their low carbon footprint and continuous energy production capacity. With the increase in wind energy investments in 2030, fossil fuels will be substituted in electricity production. In 2053, the share of wind energy in the grid will increase even more, and carbon emissions will decrease significantly.

Similarly, it will be able to provide a reducing effect on abiotic depletion potential. Hydroelectric energy is essential in Turkey's current energy mix and is critical in ensuring renewable energy supply security. In the 2030 and 2053 projections, hydroelectric energy will largely maintain its current share and be a supportive source of renewable energy targets. Turkey's geothermal energy potential is especially high in the Aegean Region and is an ideal energy source for electricity generation and heating systems. In the 2030 and 2053 projections, geothermal energy is evaluated as a replacement for fossil fuels by contributing to the sustainable energy mix and minimizing environmental impacts thanks to its low carbon emissions. Biomass energy provides dual benefits in both energy production and waste management. The use of Turkey's agricultural and forest waste for biomass energy makes

it possible to create a carbon-neutral cycle in particular. The share of biomass energy will increase in 2030 and be used as a more integrated energy source by 2053 SHURA Energy Transition Center, 2023).

In summary, the environmental impacts of fossil fuels will decrease with the increase in renewable energy sources in 2030, but further progress will be required for a complete transformation. In 2053, Turkey is expected to be dominated by solar, wind, hydroelectric, geothermal, and biomass energy sources in electricity generation, in line with its net zero carbon targets. The increase in renewable energy sources will provide improvements in environmental indicators such as global warming potential (GWP), abiotic depletion potential (ADP), and marine ecotoxicity potential (MAETP). This transformation will reduce environmental impacts and increase Turkey's energy independence, provide economic benefits, and contribute to sustainable development goals.

# 3. MATERIALS AND METHODS

In this study, a pyrolysis plant scenario providing energy and value-added products using biomass waste (hazelnut shells and apricot kernels) as raw materials in the Black Sea Region of Turkey was designed, and the life cycle assessment of the plant was carried out by considering ISO 14040 and ISO 14044 standards.

This study aims to examine the potential of creating higher economic value by producing energy, active carbon and other valuable by-products through pyrolysis instead of the current disposal method of incineration, which is the disposal method of large amounts of hazelnut shells formed as a by-product of Turkey's hazelnut production potential. In this way, it is aimed to use the biomass potential of the region in a way that supports the EU net zero targets and bioeconomy strategy and to demonstrate the effects of working with the circular bioeconomy approach. In Turkey, hazelnut shells are mostly collected in agricultural lands or hazelnut processing facilities and disposed of by traditional incineration without being utilized, and the energy value of the shells is ignored in this process. This traditional method cannot fully utilize the potential of hazelnut shells as biomass and leads to some negativities in terms of environmental sustainability.

A facility scenario was designed to obtain energy and valuable products from hazelnut shell wastes from facilities that use hazelnuts as raw materials in the Black Sea Region, where hazelnut farming is high. In this facility scenario, another raw material examined in ITU Synthetic Fuels and Chemical Technology Center, apricot kernel, was also accepted as an alternative raw material due to the similarity of their carbon contents (Hazelnut Shell: 45.5%, Apricot Kernel: 45.25%). The detailed ultimate and proximate analyses of these feedstocks are given in Appendix B. These feedstocks are preferred biomass types for pyrolysis because they have high energy density and carbon content. Their hard structure and low moisture content increase the efficiency of the pyrolysis process, while their high volatile matter content makes them a suitable raw material for energy production.

The functional unit is a standardized basis for calculation and reference, where the inputs and outputs of the system are mathematically normalized (International Organization for Standardization, 2006b). The functional unit for this system is determined as 1 kg of mixed hazelnut shell and apricot kernel mixtures / hour.

The necessary primary data were obtained from the ITU Synthetic Fuels and Chemicals Technology Center study, GaBi 8.0 software, relevant literature, and market research. The study conducted at the ITU Synthetic Fuels and Chemicals Technology Center is a THS5 level study in the Technology Readiness Levels (THS) system, a technological maturity level. This level refers to the "Integrated System Verification" stage. At this stage, technology has been brought to the prototype level and tested to work in a specific laboratory environment. This life cycle analysis (LCA) study, which was conducted using data obtained from THS 5-level projects, shows that the technology has passed the laboratory-scale verification process; that is, it has been tested in a practical environment and under realistic conditions. This clearly indicates that the study is reliable and has high sectoral validity (TÜBİTAK, n.d.).

Environmental impacts were evaluated using GaBi 8.0 software, and CML2001 impact assessment methodology was applied in four impact categories: marine aquatic ecotoxicity potential (MAETP), global warming potential (GWP), abiotic depletion potential (ADP), and human toxicity potential (HTP).

### 3.1. Goal and Scope Definition

The goal and scope definition of this study, as stated in the ISO 14044 standard, is the section where the purpose of the study is clearly stated, the functional unit, the systems to be examined, system boundaries, and the allocation procedure are explained.

This study evaluates the life cycle stages of a plant that obtains energy and valuable products from selected lignocellulosic biomass wastes. It is aimed to reveal the environmental hot spots of a pyrolysis plant that uses biomass wastes, which have high energy potential and are one of the leading renewable carbon sources, as raw materials and to provide clues on whether such pyrolysis plants can be an alternative to achieve the 2053 carbon neutrality targets and bioeconomy strategy by considering the incineration scenario, which is the current disposal management of selected biomass wastes in Turkey, as the base scenario. The European Union targets, action plans, directives, etc., to which this study aims to contribute are listed in Table 3.1.

Table 3.1. Policies Contributed by the Study.

| Strategy / Target / Action Plan / Directive | Date | Explanation |
|---|---|---|
| European Green Deal | 11 December 2019 | A comprehensive plan to make Europe the first climate-neutral continent by 2050, with a focus on sustainability and reducing emissions. The bioeconomy and waste-to-energy initiatives, like the LCA of energy and valuable product production from hazelnut shells, align with these goals. |
| Circular Economy Action Plan | 11 March 2020 | Aims to make the EU economy more resource-efficient, reduce waste, and promote sustainable products. The circular approach is relevant to the Life Cycle Assessment (LCA) of biomass waste to create energy and valuable by-products while minimizing environmental impacts. |
| Zero Pollution Action Plan | 12 May 2021 | Seeks to reduce air, water, and soil pollution to zero levels, promoting cleaner living environments. LCA studies, including those for biomass waste, help assess and minimize pollution throughout the production process of energy and valuable products. |
| Renewable Energy Directive (RED II) | 21 December 2018 | Aims to ensure that at least 32% of the EU's energy comes from renewable sources by 2030. The pyrolysis of biomass waste contributes to renewable energy production, which is a key component of this directive. |
| Waste Framework Directive | 19 November 2008 (rev. 30 May 2018) | Establishes EU rules for waste management, promoting recycling, reuse, and reducing landfill use. The LCA of hazelnut shells as a feedstock for energy and valuable products is aligned with circular economy principles and waste reduction strategies. |

Table 3.1. Policies Contributed by the Study (continued).

| Strategy / Target / Action Plan / Directive | Date | Explanation |
|---|---|---|
| EU Bioeconomy Strategy | 13 February 2012 (rev. 11 October 2018) | Focuses on boosting the EU's bioeconomy, promoting sustainable use of renewable biological resources. The conversion of biomass waste like hazelnut shells into energy and by-products fits within this strategy, contributing to sustainable resource management. |

The scope of the study covers the gate-to-gate approach for the life cycle assessment of energy and valuable products from biomass waste through pyrolysis. In this study, the experimental data sets of pyrolysis studies conducted with hazelnut shell and apricot kernel at ITU Synthetic Fuel and Chemicals Technologies Laboratory were used, and a facility scenario was developed based on the results of literature and market research. The results were evaluated by additional process integration to obtain valuable products of pyrolysis outputs.

The plant is based on circular economy principles to recover waste biomass and use resources efficiently. In addition to producing energy, activated carbon, and pyrolytic oil from biomass waste, the synthesis gas produced during the pyrolysis process is used to meet the facility's energy needs. In addition, it is aimed to reduce environmental impacts by capturing $CO_2$ in the synthesis gas, providing carbon-neutral energy production. Efficient energy integration in the plant eliminates the use of fossil fuels or external feedstocks, allowing the synthesis gases to be recycled to heat the pyrolysis reactor, convert biochar into activated carbon, and power the carbon capture unit. This route not only uses sustainable materials as a starting point but also increases the profitability of the process and converts the carbon in the feedstock material into valuable products.

Hazelnut shells, a potentially important biomass source in Turkey with an annual production amount of approximately 700,000 tons, do not have alternative uses and are continuously accumulating solid waste due to their large storage volumes. With the traditional disposal method of incineration, the potential of hazelnut shells as biomass cannot be fully utilized, which causes some problems in terms of environmental sustainability. With the pyrolysis plant scenario designed in this study, an alternative that creates higher economic value is created by allowing the production of energy, active carbon, and valuable by-products. In this study, considering these, the environmental

impacts of a pyrolysis plant that provides energy and valuable products from biomass and its current situation in Turkey were examined through a life cycle assessment over four scenarios.

The general view of the baseline scenario is given in Figure 3.1, and the general view of the plant is presented in Figure 3.2, and the description of the examined scenarios is shown in Table 3.2.

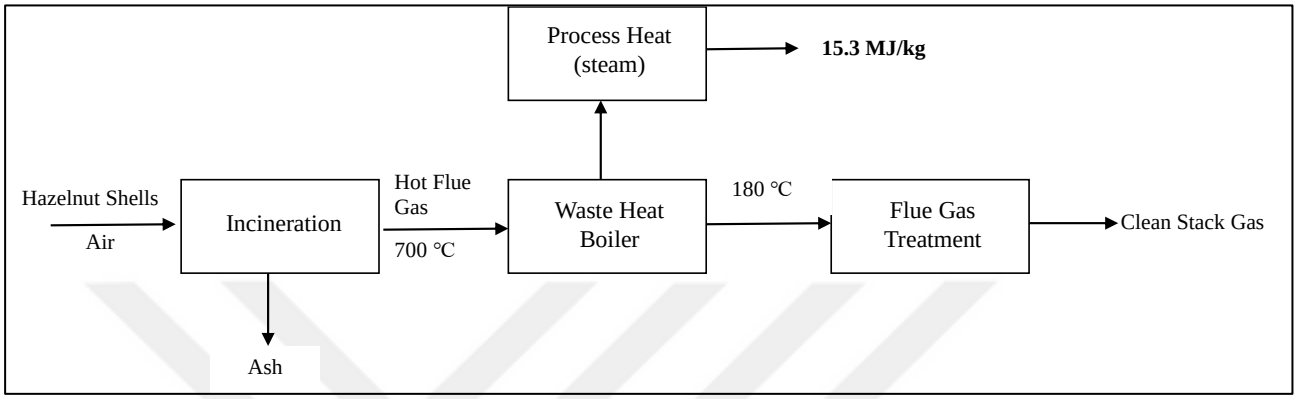


Figure 3.1. Flow Chart of Baseline Scenario

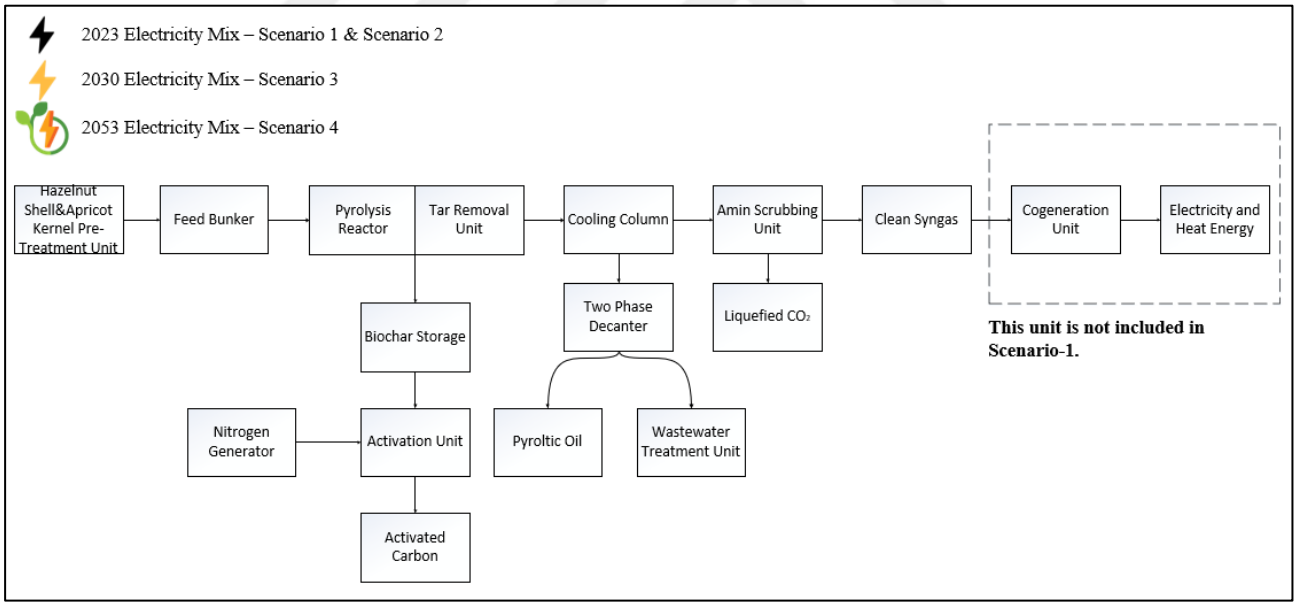


Figure 3.2. Flow Chart of Proposed Pyrolysis Plant.

Table 3.2. Scenarios of the LCA study.

| | |
|---|---|
| Base Scenario | An incineration scenario is used as the current disposal method for hazelnut shells in Turkey. |
| Scenario 1 | A biomass-waste pyrolysis plant, whose main product is high energy value syngas, converts biochar into a significant amount of activated carbon, pyrolytic liquid into pyrolytic oil, and carbon dioxide captured from syngas into liquid carbon dioxide with additional processes as a by-product. |
| Scenario 2 | A biomass-waste pyrolysis plant, whose main product is electricity and heat production, converts biochar into a significant amount of activated carbon, pyrolytic liquid into pyrolytic oil, and carbon dioxide captured from the synthesis gas into liquid carbon dioxide with additional processes as a by-product. |
| Scenario 3 | The plant capacity is expected to be doubled to that of Scenario-1, in line with the EU bioeconomy strategy and the goals of increasing the share of renewable energy in 2030 (grid mix includes nearly %40 fossil fuels and %60 renewable energy). |
| Scenario 4 | The plant capacity is increased to four times the capacity in Scenario-1, which aligns with the EU bioeconomy strategy and the target of increasing the share of renewable energy in 2053 (grid mix includes %5 of fossil fuels and %95 of renewable energy). |

In this study, as a result of the processing of the selected biomass waste in the pyrolysis plant, in addition to energy production, value-added products such as activated carbon from biochar, pyrolytic oil from pyrolytic liquid, and liquid $CO_2$ can be obtained with additional processes. One of the most valuable products of the plant is activated carbon. Activated carbon is a valuable product in many areas, such as water and air filtration, gold mining, the pharmaceutical industry, food processing, and energy storage. Considering all these, it is obvious that biomass waste utilization in such a plant scenario will definitely being advantages to Turkey's compliance for EU bioeconomy strategies.

For scenarios 3 and 4, the capacities of such a plant were increased by assuming additional plant installation in 2 and 4 different new locations, respectively. In this case, the integrated plant's production capacity for defined scenarios is clearly shown in Table 3.3. As, apricot kernels have similar calorific values with hazelnut shells, and pyrolysis results for both of them were quite closed to each other.

Scenarios 3 and 4 assess how increasing the plant's capacity by 2 and 4 times will change the system's environmental impacts in line with Turkey's changing electricity projections for 2030 and 2053 targets. The 2030 electricity mix includes nearly %40 fossil fuels and %60 renewable energy. On the other hand, in 2053, the electricity mix includes nearly %5 of fossil fuels and %95 of renewable energy. The detailed information for these electricity projections is given in Figure *2.10*. This transformation will ensure more efficient use of natural resources, reduce dependency on fossil fuels, and encourage cleaner production processes for achieving sustainable development goals and accelerating Turkey's transition to a green economy. Furthermore, the effective use of biomass waste, a key player in improving waste management and reducing the environmental footprint, is a testament to the power of circular economy principles.

Table 3.3. The Products of Proposed Plant Scenarios.

| **Output** | **Baseline Scenario** | **Scenario 1** | **Scenario 2** | **Scenario 3** | **Scenario 4** |
|---|---|---|---|---|---|
| Energy (Clean Syngas) Production (kg/year) | - | 11,379,340 | - | - | - |
| Electricity Production (MWh/year) | - | - | 17,520 | 35,040 | 70,080 |
| Heat Energy Production (MWh/year) | 101,150 | - | 17,520 | 35,040 | 70,080 |
| Activated Carbon Production (tons/year) | - | 3,994 | 3,994 | 7,989 | 15,978 |
| Pyrolytic Oil Production (tons/year) | - | 315 | 315 | 630 | 1,261 |
| Captured $CO_2$ (tons/year) | - | 4,986 | 4,986 | 9,972 | 19,944 |

Table 3.3. The Products of Proposed Plant Scenarios (continued).

| Output | Baseline Scenario | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 |
|---|---|---|---|---|---|
| Potential Impact | These energy is generally used for heating purposes | Clean syngas with 8460 kcal/kg calorific values can be used in nearby facilities as an energy source with an industrial symbiosis approach. The plant also has considerable amount of activated carbon production capacity ** | Besides the considerable amount of activated carbon production capacity, electricity generation is sufficient to meet the annual needs of 3,500 families using only 19.7% of Turkey's hazelnut shell potential* | Doubling the plant's capacity with proportional increase in output | Quadrupling the plant's capacity with proportional increase in output |
| Projections | - | Evaluated with 2023 electricity mix | Evaluated with 2023 electricity projections | Evaluated in line with 2030 electricity projections | Evaluated in line with 2053 electricity projections |

* According to TÜİK data, a family's average annual electricity consumption in Turkey is 5 MWh (TUIK, n.d.).

** According to a study conducted in 2021, Turkey's annual activated carbon import reaches 46,000 tons (Yatırım Destek ve Tanıtım Ajansı, n.d.). The facility's annual production capacity of 3,994 tons reduces the domestic production gap in Turkey, thereby lowering import dependency. In doing so, it not only supports the national economy but also aligns with EU bioeconomy strategies through the effective use of biomass. The facility's potential for activated carbon production highlights its capacity to serve as an effective alternative in Turkey's pursuit of sustainable resource use and circular economy goals.

### 3.1.1. System Boundaries

System boundaries are determined for utilization of biomass wastes in an integrated pyrolysis plant with gate-to-gate approach. The general view of the system boundaries of this study is shown in Figure 3.3. It consists of the transportation of waste to the plant, the pyrolysis process, and the processes that obtain valuable products and energy from pyrolysis products. In this study, the system inputs are energy, water, diesel, mixed feedstock, and nitrogen, while the system outputs are emissions and wastewater.

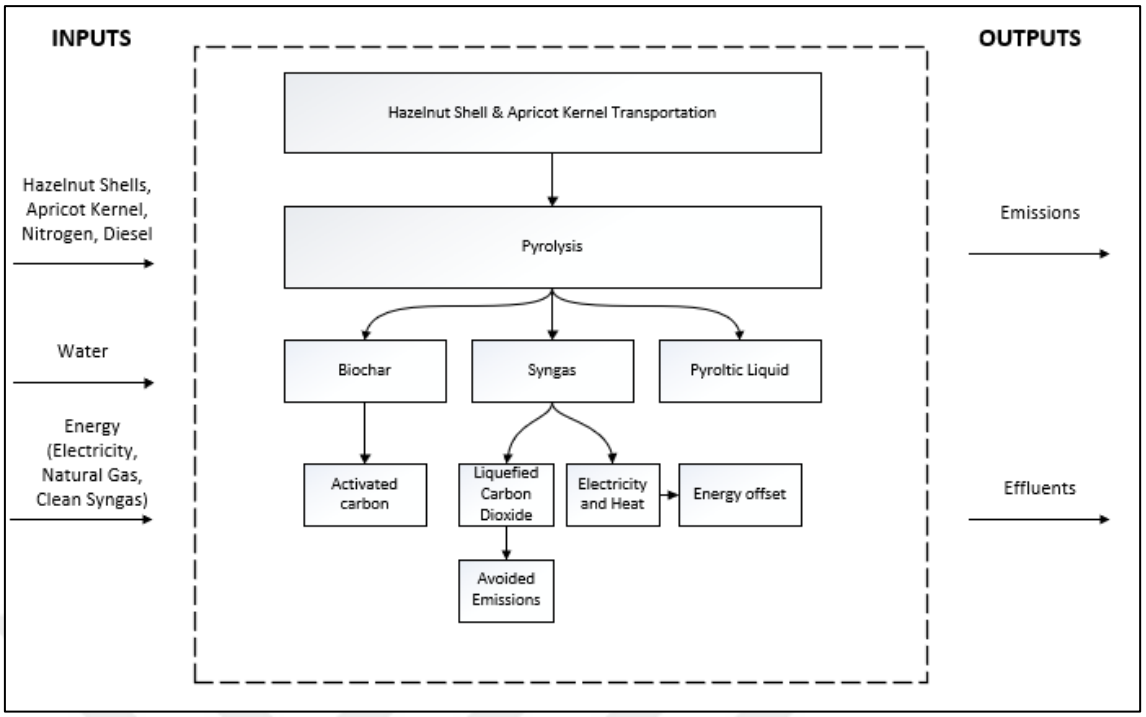


Figure 3.3. System Boundary of the Proposed Pyrolysis Plant.

The general view of the system boundary, which is given above, consists of several subsystems: transportation of biomass waste to the plant, biomass pretreatment including size reduction of raw materials, fast pyrolysis, production of activated carbon from biochar, pyrolytic oil production, amine scrubbing unit where $CO_2$ gas is removed from the syngas, and electricity and heat energy production from clean syngas. Detailed system boundaries prepared based on each product produced in this facility are shown in Figure 3.4.

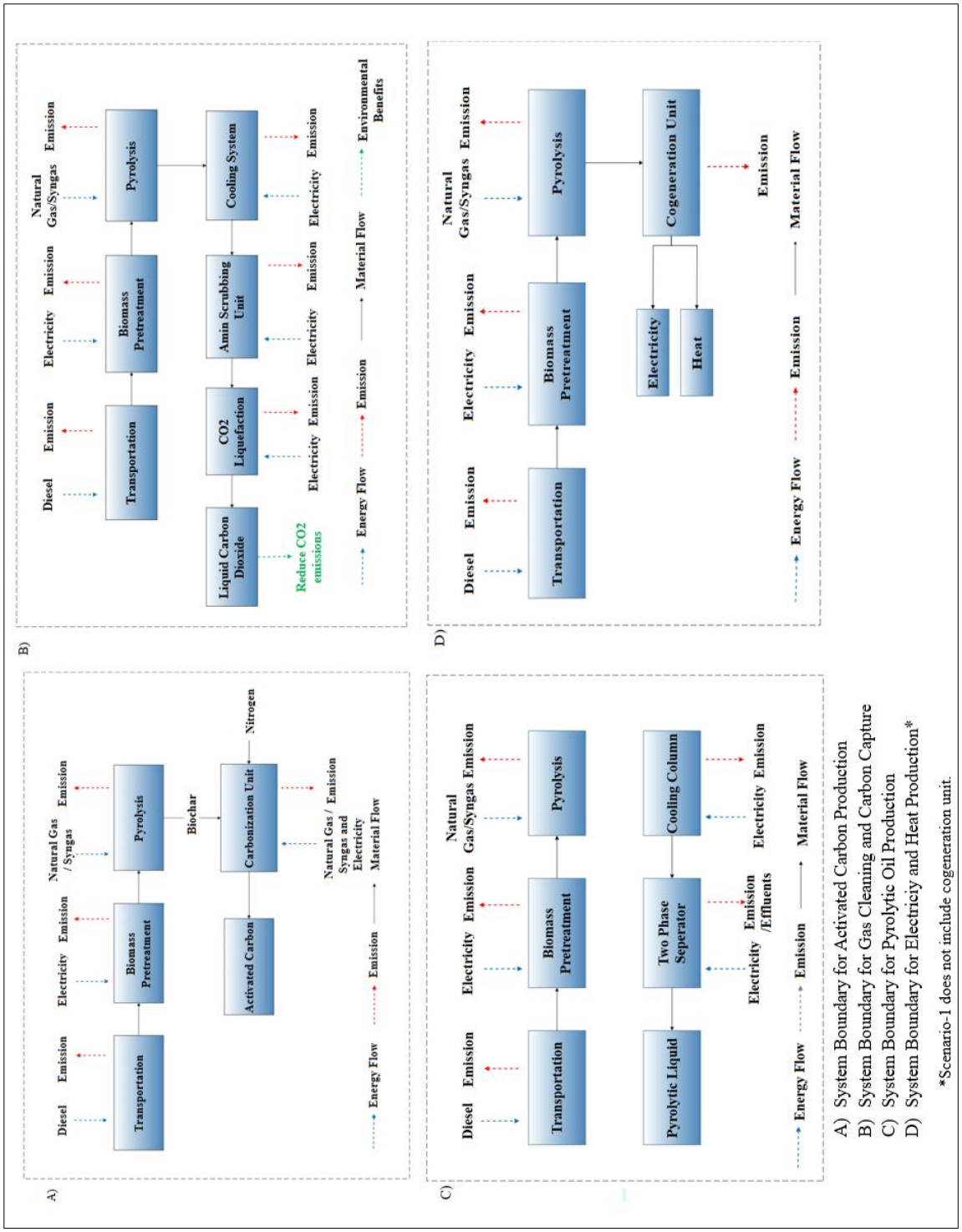


Figure 3.4. Product Based Detailed System Boundary.

*3.1.1.1.* Scenarios overview. In the 2023 scenarios, a facility with 3 tons of biomass input per hour was studied. The explanations and numerical data given in the following headings are provided for the facility in the 2023 scenario. Since the facility capacity is assumed to be doubled in the 2030 scenario, the facility continues to operate with 6 tons per hour on 2 lines, on the other hand, in the 2053 scenario, the facility capacity is assumed to be quadrupled and the facility is operated with 12 tons on 4 lines. Therefore, the inputs also increase linearly. Since the functional unit is determined as 1 kg of mixed hazelnut shell and apricot kernel mixtures/hour in this LCA study, the increase in the capacity of the facilities does not indicate a change in environmental impacts. While the scenarios show how changes in electricity projections can lead to changes in the environmental impacts of processing 1 ton of mixed biomass in such facilities over the years, the aim is to show the potential to contribute to the EU Green Deal in line with the bioeconomy strategy by presenting product-based results of evaluating the existing biomass potential in Turkey in such facilities with capacity increases.

*3.1.1.2.* Feedstock pretreatment. In the first stage, feedstocks, consisting of hazelnut shells and apricot kernels, are transported to the plant by a diesel truck. The feedstocks, a mixture of these biomass wastes, carried to the plant are generally 0.5-1 cm. Capacity increase scenarios are designed to operate the facility in the same region over two lines in 2030 and 4 lines in 2053. Accordingly, changing truck sizes for the transportation of increased inputs is also integrated into the scenarios on the software. The raw materials are subjected to biomass pre-treatment to prepare for feeding to the pyrolysis reactor. Here, the grain sizes are reduced to 0.2-0.4 cm by passing the feedstocks through shell crushers powered by electricity. During the crushing process, the powders occurred from dusting, are collected by filters, mixed with crushed shells, and fed to the pyrolysis reactor. Therefore, no waste occurs in the biomass pre-processing unit.

*3.1.1.3.* Pyrolysis process. The pyrolysis reactor is heated with 65 $Nm^3$/hr natural gas at the first start-up. As a result of approximately 3-4 hours of heating, the temperature inside the reactor is brought to 850 ℃, and the mixture of hazelnut shells and apricot kernels are fed to the pyrolysis reactor. After this point, the energy requirement of the pyrolysis reactor begins to be obtained from the synthesis gas produced by the plant. The pyrolysis process is carried out with a screw pyrolysis system. In screw pyrolysis systems, feedstocks are placed in a drum and advanced through screws inside this drum. During the process, the feedstock is heated to 850 ℃ in an oxygen-free environment to initiate the thermal decomposition process in this system with a rotation speed of 10 RPM.

*3.1.1.4.* Product utilization. The biochar produced from the pyrolysis reactor is conveyed to the biochar tank for subsequent transfer to the activated carbon production unit. The activation process of the facility is carried out in a rotary kiln with a diameter of 0.75 m and a length of 6 m using the physical activation method with nitrogen gas with a flow rate of 2400 $m^3$/h. The nitrogen used here is obtained from PSA type nitrogen generators. The biochar and the physical activation agent nitrogen fed into the reactor are moved along a rotating cylinder in the reactor and are heated by the heat source inside the kiln simultaneously. Thanks to the heat, the materials enter the carbonization process, and after the active carbon production is completed, the obtained product is removed from the other end of the kiln. While the energy needs of the rotary kiln reactor in the activation unit are met from the synthesis gas produced in the system, the nitrogen generator consumes electricity. Produced activated carbon is sold for use in many areas, from wastewater treatment to the pharmaceutical industry.

The synthesis gas is passed through the tar removal process operated at 600-700 ℃. During the start-up period energy for the tar removal is obtained from natural gas as synthesis gas production starts is obtained from synthesis gas. In tar removal, high-molecular compounds in the tar structure in the gas phase are broken into small molecules by cranking. The synthesis gas coming out here contains $CO_2$, $CH_4$, $H_2$ and CO. With the tar removal process, the amount of valuable gases such as $H_2$ and $CH_4$ in the synthesis gas composition increases.

After tar removal, the synthesis gas is passed through the cooling system. The temperature of the synthesis gas entering the cooling column at an average temperature of 400 - 500 ℃ is cooled down to 25-30 ℃. A heat exchanger is used to separate and purify the syngas, a gaseous byproduct of pyrolysis. This is where the syngas and chilled water interact. The water comes from a chiller. The heat exchanger helps to separate the gases and liquids by cooling the mixture during this operation. Here, large molecules that can condense in the cooled gas become pyrolytic liquid. Crude pyrolysis liquid with a 360 kg/hr flowrate (in 2023 scenarios) contains 90% water and 10% oil. This oil-liquid mixture is sent to the two-phase separator to produce pyrolytic oil, a valuable product that can be used in industrial applications and biodiesel production. Here, the separated water phase is sent to the wastewater treatment unit to meet the region's discharge criteria. The energy needs of two-phase separators are met by electricity.

After separating the oil phase from the pyrolytic liquid, the remaining water with a 324 kg/hr flowrate is sent to the wastewater treatment unit to be treated in accordance with regional discharge criteria. Literature results indicate that due to increasing discharge restrictions in recent years,

electrocoagulation systems with high treatment efficiency have gained importance in the treatment of wastewater with high organic content. The working principle of the electrocoagulation process is carried out by applying an electric current to the water through electrodes. In this process, dissolved and suspended pollutants in the water are coagulated with the help of metal ions (usually aluminum or iron) and form larger particles. The resulting flocs are then removed from the water by filtration or sedimentation. Literature studies have shown that the efficiency of electrocoagulation can reach up to 98% for COD (Yılmaz & Karagözoğlu, 2019).

After this stage, the synthesis gas in the system contains $H_2$, $CO_2$, CO, and $CH_4$. Synthesis gas is transmitted to the amine scrubbing unit to remove the $CO_2$ contained in the synthesis gas from the system. This unit consists of preparing a liquid amine solution and absorber and desorber columns. This unit uses monoethanolamine (MEA), a liquid amine solution with a solution concentration of 15% by weight in water, to capture $CO_2$. The amine solution is contacted with gas in a countercurrent column and absorbs $CO_2$. The $CO_2$-rich amine stream coming out of the absorber bottom is regenerated in the regeneration column (desorber), and by heating the solution, pure $CO_2$ is released while the MEA is regenerated (Rosental et al., 2020). The columns enable the continuous regeneration of the amine solvent, thereby minimizing solvent losses. The $CO_2$ removed from the synthesis gas is liquefied through cooling and compression. This process is particularly important for the efficient storage and transportation of $CO_2$ in carbon capture and storage (CCS) applications. In this scenario, the liquefied $CO_2$ is assumed to be used as raw material in a nearby plant through an industrial symbiosis approach. In this way, it aims to minimize the system's environmental impacts while contributing to the circular economy.

This study considered energy production from the obtained clean synthesis gas with two different options. One option includes using the high calorific value clean synthesis gas with a calorific value of 8460 kcal/kg as a direct energy source in nearby facilities. Laboratory results have shown that the calorific value of this clean synthesis gas is close to the calorific value of natural gas. Therefore, using this gas as an energy source is a good way to reduce the system's abiotic depletion potential. Another option includes integrating a cogeneration unit to obtain electricity and heat from the clean synthesis gas obtained after the amine washing unit. The air and synthesis gas mixture drives an electric generator in the cogeneration system. The high-temperature exhaust gases from the gas turbines are used in the waste heat boiler to obtain high-efficiency heat energy. In this way, electricity and heat production are achieved from the synthesis of gas. Using the technical specifications of the gas engines, heat and electricity efficiency was considered as equal. This result has also been compared with cogeneration units in the literature. Research indicates that the efficiency of electricity

generation in thermal power plants does not exceed 30–40%, while cogeneration enables dual production, achieving high efficiencies of 80–90% (Pravadalıoğlu et al., n.d.). Furthermore, studies examining energy production facilities using similar gas engine types reveal that electricity and heat production efficiency align with the ratios specified in the technical specifications (Saltabaş & Yalçin, 2004).

*3.1.1.5.* Incineration of hazelnut shells. The base case scenario for hazelnut shell incineration involves transporting hazelnut shells to the incineration plant and burning them. No direct energy input is required for the incineration of hazelnut shells; however, a small amount of energy may be needed to initiate combustion. This is usually limited to the energy used for ignition. Therefore, the energy consumption for incineration is ignored. Since the functional unit was selected as 1 kg/hr mixed feedstock in the facility scenarios, the burning scenario of hazelnut shells was also evaluated based on 1 kg/hr of hazelnut shells.

The energy released by burning hazelnut shells in Turkey can be used for various purposes. In rural areas, hazelnut shells can be used to produce heat for individual use. Hazelnut shells are also used for heating purposes by burning them in systems similar to traditional wood stoves. Moreover, some textile factories in Turkey provide process heat by burning biomass waste instead of fossil fuels such as coal. The process scheme for this option is demonstrated in Figure *3.1*. Hazelnut shells are converted into energy by incineration with an energy content of 18 MJ/kg. Steam conversion rate is approximately 85% so, energy content of the steam is nearly 15.3 MJ/kg. In this process, hazelnut shells are burned to obtain heat energy. The heat released during the incineration process is collected in a waste heat boiler and evaluated as process heat, and steam production is provided. This steam produced can also be used as process heat, especially in energy-intensive sectors such as the textile industry. Flue gases, another output of the incineration process, are directed to the flue gas treatment unit at 180°C and are released into the environment after being purified from harmful substances.

## 3.2. Life Cycle Inventory Analysis

Life cycle inventory analysis (LCI) is the stage where system models are created and all input and output data throughout this cycle are collected and calculated (International Organization for Standardization, 2006b). Inventory analysis is an essential stage of LCA because it creates datasets encompassing all energy, material, and waste flows associated with environmental impacts. The data

collected and calculated, along with the data sources, for use in the LCI stage of this study are presented in Table 3.4 on a subsystem basis. Detailed inventory data is also shown in the Appendix.

Table 3.4. Stage-based Inventory Data and Data Sources.

| Stage | Required Data | Data Sources |
|---|---|---|
| S1; Pyrolysis Stage | Diesel consumption, electricity consumption, feedstock amount, natural gas consumption, amount of recycled syngas, the amount of produced biochar, syngas and pyrolytic liquid | GaBi 8.0 software, ITU Synthetic Fuels and Chemicals Laboratory, market research results |
| S2; Active Carbon Production Stage | Natural gas consumption, amount of recycled syngas, the amount of biochar, nitrogen demand, the amount of produced activated carbon | GaBi 8.0 software, ITU Synthetic Fuels and Chemicals Laboratory, market research results |
| S3; Pyrolytic Oil Production Stage | Natural gas consumption, electric consumption, amount of produced wastewater, amount of produced pyrolytic oil | GaBi 8.0 software, ITU Synthetic Fuels and Chemicals Laboratory, market research results, literature results (Zulkafli et al., 2023) |
| S4; Gas Cleaning Stage | Amount of consumed MEA, electricity consumption, amount of captured $CO_2$, amount of syngas, amount of produced clean syngas | GaBi 8.0 software, ITU Synthetic Fuels and Chemicals Laboratory, literature results (Rosental et al., 2020) |
| S5; Electricity Production Stage | Amount of consumed clean syngas, amount of produced heat energy, amount of produced electricity, amount of produced heat energy, exhaust emissions values | GaBi 8.0 software, market research results, literature results |
| S6; Incineration Stage | Amount of produced energy, emission values | Literature results |

The pyrolysis stage involves transporting biomass waste to the plant to obtain the main products. This study assumes that the plant is located in an organized industrial zone in the Black Sea Region, considering the proximity to the raw material. In the proposed scenario, it is assumed that biomass waste is collected from collection points and delivered to the plant by diesel trucks, which contributes to greenhouse gas emissions. The diesel consumption for these vehicles is 3.2 liters per kilometer, and the distance between the plant and the feedstock collection point is assumed to be 10 kilometers.

Upon arrival at the plant, the feedstocks are fed into the biomass pre-treatment unit. The crushing machine used in the pre-treatment process consumes 60 kWh of energy for every 3000 kg of input. Scenario-based electricity mix projections for 2023, 2030, and 2053 were used for the electricity consumption in this life cycle analysis study.

Following the pre-treatment unit, the feedstocks adapted to the pyrolysis reactor are fed into the screw pyrolysis system. The feedstock is heated to 850 °C in an oxygen-free environment, initiating the thermal decomposition process in this system with a rotation speed of 10 RPM. The system consumes 130 $Nm^3$ of natural gas during the initial start-up period of approximately 3 hours. Subsequently, the energy requirement of the pyrolysis reactor is met by the clean synthesis gas produced within the system. Based on calculations considering the calorific value of the clean synthesis gas, the pyrolysis reactor's hourly clean synthesis gas demand is calculated to be 117 kg.

After the pyrolysis process, biochar is utilized within the plant to produce activated carbon, a value-added product. The biochar yield from the pyrolysis system is 20% for hazelnut shells and 18% for apricot kernels, resulting in 570 kg of biochar being directed to the carbonization unit. This unit employs physical activation with nitrogen in rotary kilns. Laboratory results indicate a nitrogen requirement of 2400 $m^3$/hr. To ensure a reliable and efficient nitrogen supply, PSA-type nitrogen generators are used, as direct purchase of nitrogen is impractical due to diesel consumption and potential supply chain disruptions. These generators operate on 500 kWh of electricity and use pressure swing adsorption (PSA) technology to extract nitrogen from atmospheric air, with air demand calculated based on the nitrogen content in the air.

The rotary kiln reactors, characterized by their long cylindrical structure, facilitate carbonization. Biochar and nitrogen are introduced into the kiln, where they are subjected to high temperatures generated by the internal heat source, promoting carbonization. The energy demand of the kiln is 40

kg/hr, met by clean syngas produced within the system, with natural gas used for startup. The activated carbon is extracted from the opposite end of the kiln after the activation process.

Synthesis gas, a by-product produced primarily as a result of pyrolysis, is passed through the tar removal unit operated at 600-700 °C. In this study, the tar removal unit and pyrolysis process were shown together in all flows, and their energy needs were evaluated together. After the tar is removed, the synthesis gas is passed through the cooling unit. The temperature of the synthesis gas entering the cooling column at an average temperature of 400-500 °C is cooled to at least 25-30 °C. The cooling unit consists of a chiller and a heat exchanger. The electricity consumption of this system is 50 kWh. Since the water entering the heat exchanger is used repeatedly, the water consumption is ignored.

During the cooling process, large molecules in the cooled gas condense into pyrolytic liquid. Crude pyrolysis liquid contains 90% water and 10% oil phase. A two-phase separator is used to separate these oil and liquid phases to obtain valuable pyrolytic oil. According to market research conducted to determine the energy consumption of separators for systems of this size, the energy consumption of the separator was determined to be 30 kWh.

The water phase separated here is sent to the wastewater treatment unit to be purified to meet the discharge criteria of the region. Electrocoagulation is used in the wastewater treatment unit. According to market research conducted to determine the energy consumption of electrocoagulation systems of this size, the energy requirement for electrocoagulation treatment in this plant is determined to be 6 kWh.

The synthesis gas produced by pyrolysis contains $H_2$, $CO_2$, CO, and $CH_4$. To remove the acidic gas $CO_2$, synthesis gas is sent to an amine scrubbing unit, which consists of preparing a liquid amine solution and absorber and desorber columns. In this system, a liquid amine solution, monoethanolamine (MEA), is used to capture $CO_2$. The amine solution contacts the gas in a counter-current column to absorb $CO_2$; the $CO_2$-rich amine flow from the absorber base is regenerated in the desorber column, where heating renews the MEA and releases pure $CO_2$. Amine scrubbing uses energy in the absorption and desorption processes. Energy is consumed for pumping and mixing the gas during absorption and heating during desorption. Studies on amine scrubbing using MEA in the literature were reviewed to determine this energy requirement. The literature indicates an energy demand of 3.9 to 4.2 MJ/kg of captured $CO_2$. For this life cycle assessment, the unit's energy demand was assumed to be 4 MJ/kg $CO_2$, and the total energy requirement for the amine scrubbing system

was calculated using the $CO_2$ capture rate obtained from laboratory results. Another input for this unit is the amount of MEA(Rosental et al., 2020) report that 2 kg of MEA is needed to capture 1 ton of $CO_2$. Therefore, the hourly MEA requirement for this system, which captures 569 kg of CO2 per hour, is calculated to be 1.14 kg (569 kg captured $CO_2$ * 2 kg MEA/captured ton $CO_2$). The water used to prepare the liquid MEA solution is ignored as it can be repeatedly reused in the system. In the next stage, the captured $CO_2$ is subjected to liquefaction for ease of transportation and storage. The literature research indicates that the energy requirement for $CO_2$ liquefaction varies between 105 kWh/ton $CO_2$ and 115 kWh/ton $CO_2$. Therefore, this study uses an assumed energy consumption of 110 kWh/ton $CO_2$ for the plant's $CO_2$ liquefaction process (Zahid et al., 2014).

Another unit included in scenarios 2, 3, and 4 in the system is the cogeneration unit, which produces electricity and heat energy from synthesis gas. The input value for the cogeneration unit was calculated by subtracting the amount of clean synthesis gas consumed for the energy needs of the units in the plant from the amount of clean synthesis gas obtained in the amine scrubbing unit.

Table 3.5. The Input Data for Proposed System.

| **Process** | **Input Data** | **Quantity** | **Selected Flow from GABİ 8.0** |
|---|---|---|---|
| Transportation | Diesel consumption | 3.2 lt/km | Diesel [Refinery products] |
| Biomass Pre-treatment | Mixed feedstock | 3000 kg | Mixed feedstock [Biomass] |
| | Electricity consumption** | 60 kWh | Electricity [Electric power] (SHURA Energy Transition Center, 2023) |
| Pyrolysis | Mixed feedstock | 3000 kg | Mixed feedstock [Biomass] |
| | Natural gas consumption | 130 $Nm^3$ (for 3 hr) | Natural gas Turkey |
| | Clean syngas consumption | 117 kg/hr | Clean syngas [Valuable Substances] |
| Biochar Storage | Biochar | 570 kg/hr | Bio-char [Valuable substances] |

| Process | Input Data | Quantity | Selected Flow from GABİ 8.0 |
|---|---|---|---|
| Carbonization Unit | Clean syngas consumption | 40 kg/hr | Clean syngas [Valuable Substances] |
| | Biochar | 570 kg/hr | Bio-char [Valuable substances] |
| | Nitrogen | 2400 $m^3$ | Nitrogen gaseous [inorganic intermediate] |
| Nitrogen Generator | Atmospheric air | 3077 $m^3$ | Air [Renewable resources] |
| | Electricity consumption** | 500 kWh | Electricity [Electric power] |
| Cooling Unit | Amount of Pyrolytic Liquid | 360 kg | Pyrolytic liquid [Valuable substance] |
| | Electricity Consumption** | 50 kWh | Electricity [Electric power] (SHURA Energy Transition Center, 2023) |
| Two Phase Separator | Amount of Pyrolytic Liquid | 360 kg | Pyrolytic liquid [Valuable substance] |
| | Electricity Consumption** | 30 kWh | Electricity [Electric power] (SHURA Energy Transition Center, 2023) |
| Wastewater Treatment | Wastewater Amount | 324 kg | Wastewater [Production residues in life cycle] |
| | Electricity Consumption** | 6 kWh | Electricity [Electric power] (SHURA Energy Transition Center, 2023) |
| | Amount of Syngas | 2070 kg | Syngas [Valuable substances] |

| Process | Input Data | Quantity | Selected Flow from GABİ 8.0 |
|---|---|---|---|
| Amin Scrubbing & Amine Regeneration Unit | Mono ethanol amine amount | 1.14 kg | Mono ethanol amine [organics] |
| | Water | 7.4 kg | Washing water [Others] |
| | Clean syngas consumption | 45 kg | Clean syngas [Valuable Substances] |
| $CO_2$ Liquefaction | Amount of captured $CO_2$ (g) | 569 kg | Carbon dioxide [Renewable resources] |
| | Electricity Consumption** | 110 kWh/kg$CO_2$ | Electricity [Electric power] (SHURA Energy Transition Center, 2023) |
| Cogeneration Unit* | Clean syngas | 1299 kg | Clean syngas [Valuable Substances] |

*There is no cogeneration unit in Scenario 2.

**Scenario 3 and Scenario 4 contain the same stages as Scenario 1 as input. In Scenario 3, all values are taken as times two since the system capacity is doubled. In Scenario 3, the electrical mix is prepared in GaBi 8.0 software according to 2030 energy mixes and is included in Scenario 3. In Scenario 4, all values are taken as four times since the system capacity is increased by 4. In Scenario 4, the electrical mix is prepared in GaBi 8.0 software according to 2053 energy mixes and included in Scenario 4.

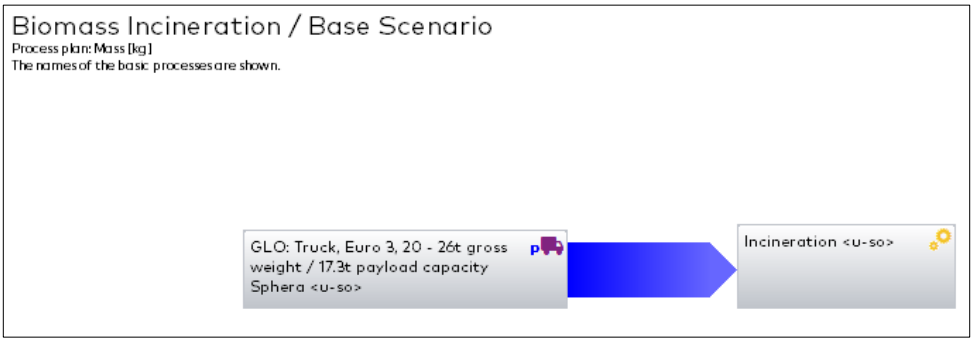


Figure 3.5. LCA Flow for Base Scenario.

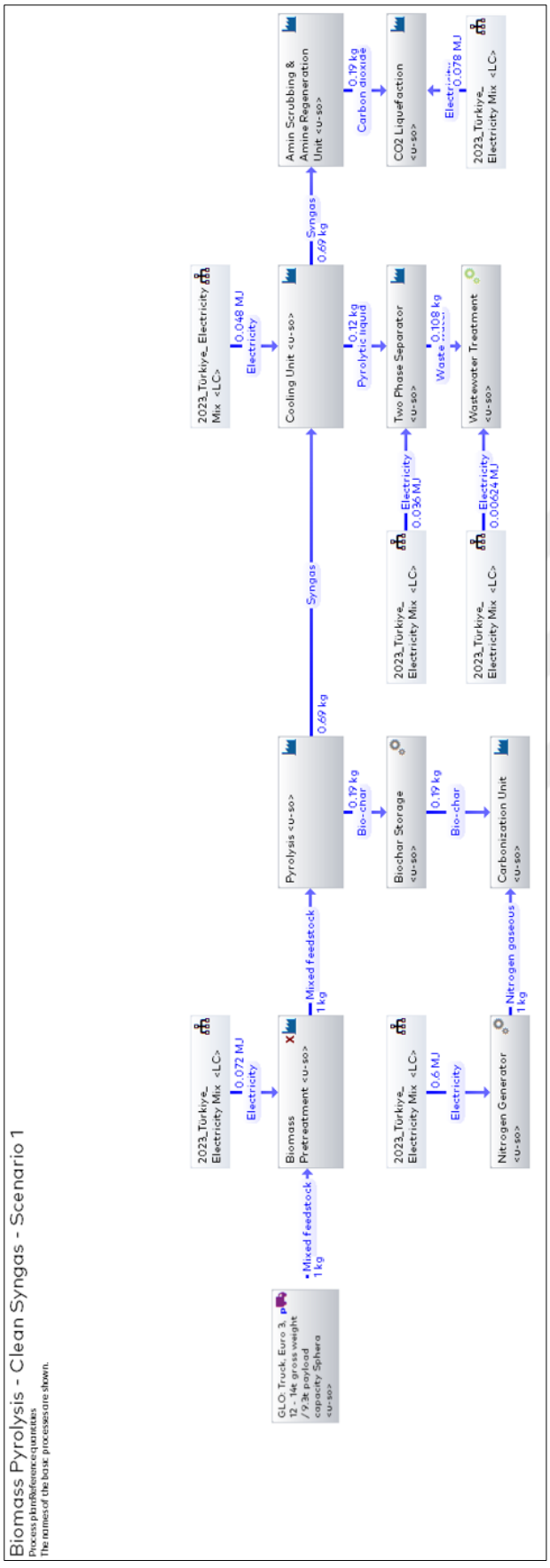


Figure 3.6. LCA Flow for Scenario – 1.

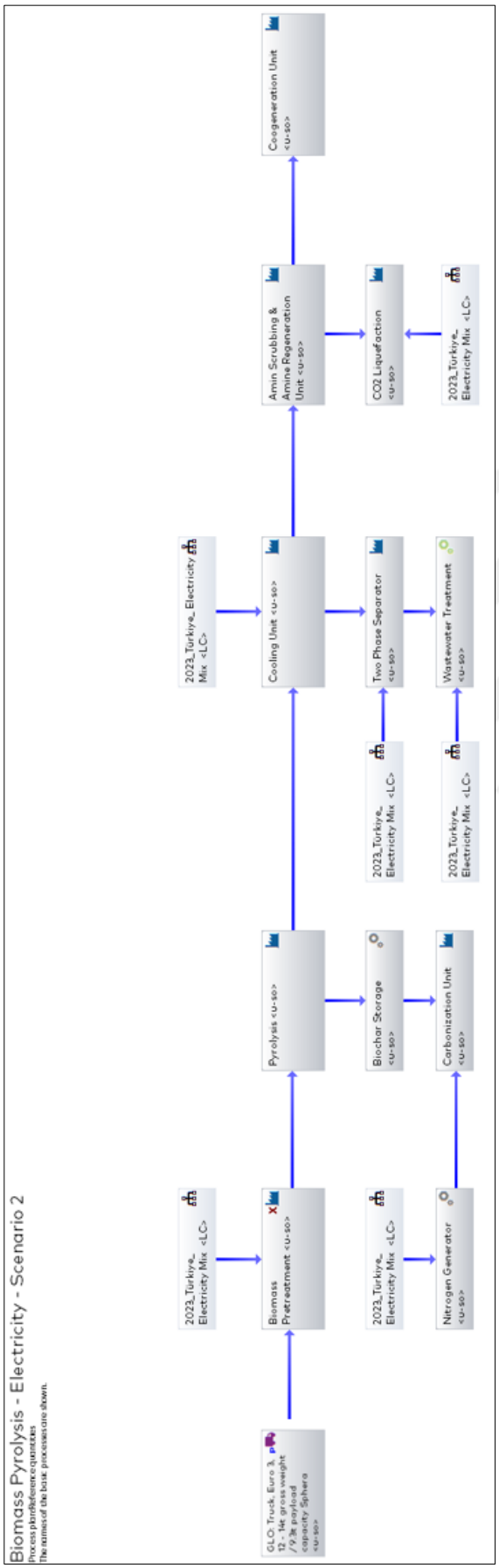


Figure 3.7. LCA Flow for Scenario – 2.

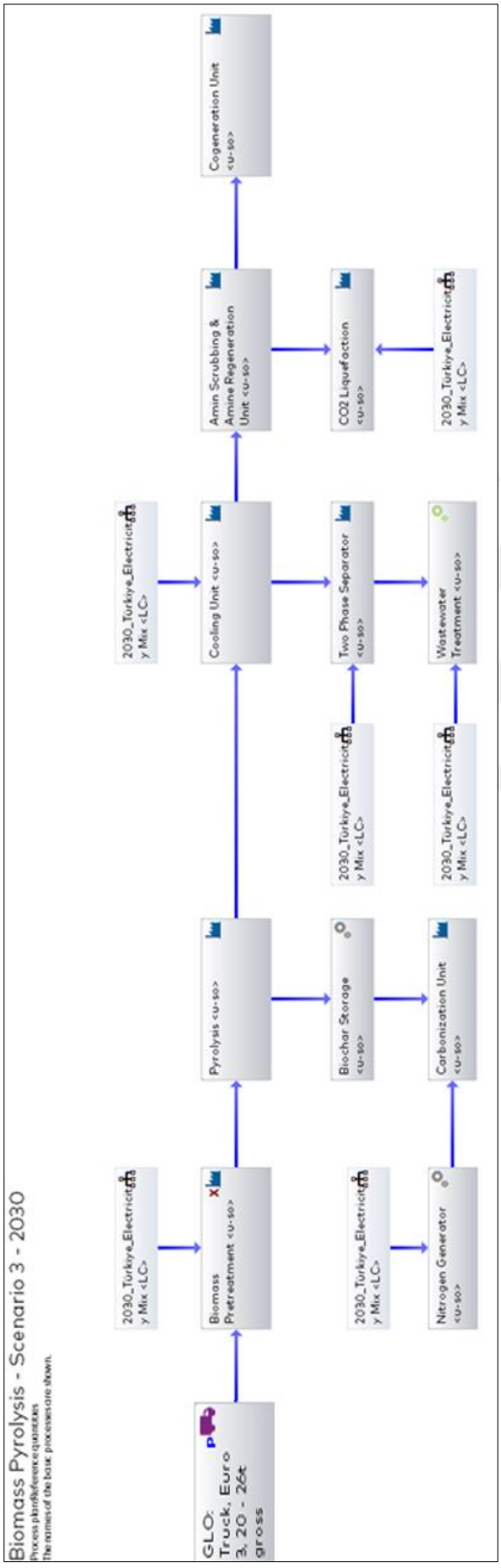


Figure 3.8. LCA Flow for Scenario – 3.

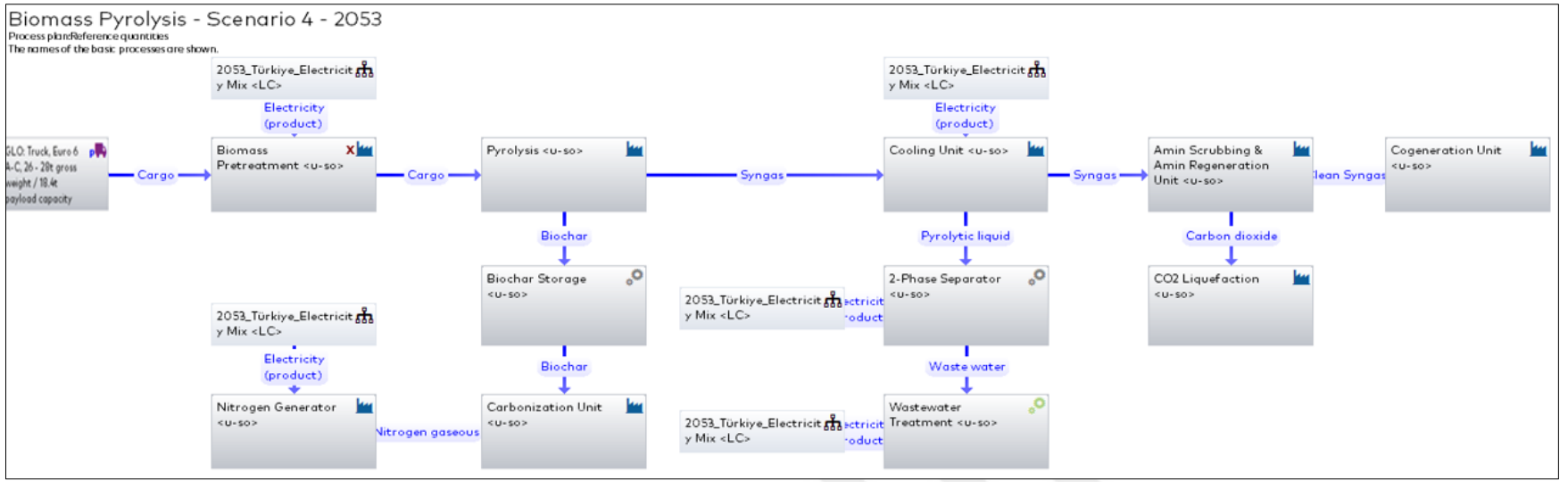


Figure 3.9. LCA Flow for Scenario – 4.

# 4. RESULTS AND DISCUSSION

## 4.1. Life Cycle Impact Assessment

Life Cycle Impact Assessment (LCIA) is the process of understanding and evaluating the magnitude and significance of potential environmental impacts throughout the life cycle of a product system. The results of LCIA should be associated with limitations within the defined scope and purpose. Additionally, consideration should be given to how LCIA results are related to the defined purpose and scope, their relationship with Life Cycle Inventory (LCI) results, impact categories, and category indicators (International Organization for Standardization, 2006b). In this LCA study, the classification, normalization, and characterization steps of LCIA were carried out, taking into account the stages of ISO 14044.

CML, IPCC, ReCiPe, and ILCD are the widely used and accepted impact assessment methodologies in LCIA studies. CML methodology is the most used methodology in environmental impact assessment among these methods (Rapa & Ciano, 2022). The CML methodology used in this LCIA study is a procedure used to measure the environmental impacts caused by systems. The CML 2001 approach was developed by researchers at the Leiden University Centre for Environmental Science in 2001. It proposes a set of characterization methods and impact categories for evaluating environmental effects (Gong et al., 2015).

In an LCA study, when classifying LCI results according to impact categories, it is necessary to define LCI results specific to a single impact category and related to more than one impact category (International Organization for Standardization, 2006b).

In the classification step of the study, life cycle inventory results were assigned to different impact categories. The impact categories in this study are marine aquatic ecotoxicity potential (MAETP), global warming potential (GWP), abiotic depletion (ADP), and human ecotoxicity potential (HTP), as shown in Table 4.1. The baseline scenario includes the transportation of raw materials to the facility and the incineration stages. Since the transportation stage is common to all scenarios, the baseline scenario was evaluated only for the GWP potential caused by incineration.

Table 4.1. Selected Impact Categories of the Study.

| Impact Categories | Unit |
|---|---|
| Marine Aquatic Ecotoxicity Potential (MAETP inf.) | [kg DCB eq.] |
| Global Warming Potential (GWP 100 years) | [kg $CO_2$ eq.] |
| Abiotic Depletion (ADP fossil) | [MJ] |
| Human Toxicity Potential (HTP inf.) | [kg DCB eq.] |

There may be some uncertainties or limitations that may affect the interpretation of the findings in LCA studies. These may be mainly data sources and quality, modeling assumptions, or geographical and temporal boundaries. When we evaluate this study specifically, since the data were primarily taken from ITU Synthetic Fuels and Chemicals Laboratory and evaluated on a facility basis, high-quality and reliable data input was provided. In addition, since the inputs used for active carbon production, pyrolytic oil production, and carbon capture units were developed with literature information and market research, there may be uncertainties regarding matching these data to actual facility conditions. The assumptions made in LCA studies, especially in matters such as energy sources, process efficiency, or scenario selection, may affect the reliability of the results. Forecasts such as Turkey's electricity projections for 2030 and 2053 assume that environmental impacts will decrease as electricity sources shift to renewable energy. However, the possibility that these projections will not be realized, or deviations may reduce the accuracy of the results. In addition, considering that the study was conducted for a specific region, changes in wastewater discharge criteria and access to raw materials or biomass sources may produce different results in a different area or future applications.

### 4.1.1. Characterization

In this step, to evaluate the environmental impacts of the data flows obtained from the inventory analysis, they were classified according to specific impact categories, and the magnitudes of these impacts were measured.

Biomass waste refers to organic materials (e.g., agricultural residues, food waste, forest products, animal waste) that remain after being used or processed and are no longer intended for primary production or consumption purposes (Wang & Tester, 2023). Management of these wastes is one of the significant challenges faced globally in achieving the Sustainable Development Goals (SDGs). In this study, biomass wastes were used as feedstock for the designed facility. The conversion of such wastes into energy and value-added products can contribute significantly to recovering potential

economic value and resources, as shown in this study. In this context, the study evaluates the environmental impacts of establishing such a facility in 2023 and presents the projected results for the 2030 and 2053 scenarios. These projections are made in the context of the EU Green Deal and bioeconomy strategy goals, examining how increased plant capacities might change the outcomes.

To meet the energy needs of the system, the effects were examined through plant scenarios where clean synthesis gas with a composition of 53% $H_2$, 25% CO, and 22% $CH_4$ and a calorific value of 8460 kcal/kg was used instead of natural gas after the start-up period. For the electricity use of the system, background information on Turkey's electricity mix in 2030 and 2053 was accepted with the emission factor and integrated into the scenarios.

The results show that marine aquatic ecotoxicity potential (MAETP) is a significant impact category, with Scenario 1 and Scenario 2 having the highest values at 11,670 kg DCB equivalent. In contrast, Scenario 3 and Scenario 4 have 7,134 and 3,580 kg DCB equivalent, respectively, decreasing by 39% and 69% compared to Scenario 1. Abiotic Depletion (ADP fossil) is 1.29 MJ when examined for Scenario 1 and Scenario 2. In comparison, it is 0.89 MJ in Scenario 3, with a 31% decrease compared to Scenario 1, and 0.24 MJ in Scenario 4, with an 81% decrease compared to Scenario 1. Global warming potential (GWP 100 years) is highest in Scenario 2 at 1.740 kg $CO_2$ eq., followed closely by Scenario 3 at 1.709 kg $CO_2$ eq. and Scenario 4 at 1.661 kg $CO_2$ eq., with Scenario 1 having the lowest at 0.24 kg $CO_2$ eq. HTP inf. shows relatively low values across all scenarios, with Scenario 2 being the highest at 0.0056 kg DCB eq. and Scenario 4 the lowest at 0.0041 kg DCB eq. A detailed examination of the results of these impact categories will be given in the following sections.

*4.1.1.1.* Marine aquatic ecotoxicity potential (MAETP). Marine Aquatic Ecotoxicity Potential is an environmental impact assessment indicator that measures a product's or process's potential harmful effects on marine ecosystems. Marine Aquatic Ecotoxicity Potential is measured as kg DCB equivalent (Marzeddu et al., 2021).

The MAETP results of this LCA study are presented scenario-based in Figure 4.1.

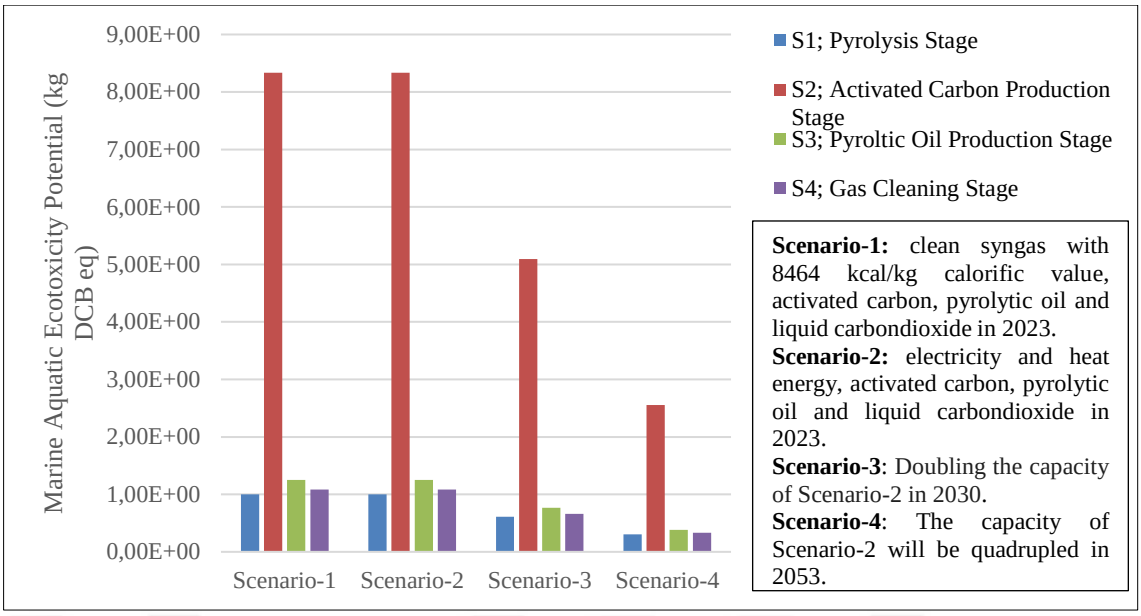


Figure 4.1. Quantified Marine Aquatic Ecotoxicity Potential.

Taking into account to LCIA, it has been observed that marine aquatic ecotoxicity potential is a significant impact category. This potential is directly attributed to the plant's electricity consumption. In Turkey, electricity mixes include fossil fuels, nuclear energy, and renewable energy sources (Ministry of Energy and Natural Resources of Turkey, 2024). Various chemical groups contribute to marine aquatic toxicity potential depending on the energy sources used in electricity generation. Heavy metals such as polyaromatic hydrocarbons (PAHs), mercury, lead, cadmium, and radioactive isotopes are released during the combustion of fossil fuels and nuclear energy production and can enter aquatic ecosystems and cause toxic effects on organisms there. Furthermore, acid rain—a byproduct of burning fossil fuels—and nitrogen oxides (NOx) and sulfur dioxide ($SO_2$) can have a negative impact on marine ecosystems. Depending on the type of electricity generated, the presence of these chemical groups determines how power generation affects marine environments. (Gaete-Morales et al., 2019). Renewable energy sources generally have lower pollutant emissions, but their production and installation processes can impact aquatic habitats. Therefore, electricity consumption is directly related to aquatic ecotoxicity (Tomczyk et al., 2021).

When we look at the results, it is seen that the cogeneration step has no effect on the marine aquatic toxicity potential, and the results are equal to 11,670 kg DCB in Scenario 1 and Scenario 2. On the other hand, thanks to Turkey's changing electrical projection, the MAETP result decreases to 7,134 kg DCB in Scenario 3 and drops to 3,580 kg DCB in 2050. Efficiency gains in energy generation technologies and a decarbonized grid reduce the environmental impacts of electricity use in processes.

Upon examining the production steps of the plant, it is observed that the largest contribution to MAETP occurs in the activated carbon production stage. The primary factor here is the PSA nitrogen generators used for nitrogen production from air, a process with high electricity consumption. Following this step, the next significant contribution to MAETP comes from the pyrolytic oil production stage, which includes electricity consumption for cooling, two-phase separation, and the use of electrocoagulants in the wastewater treatment unit. The consumption items in this stage contributing to MAETP are measured in the order of Cooling Unit > Two Phase Separator > Wastewater Treatment Unit.

The 3$^{rd}$ and 4$^{th}$ contributors to this impact category are the gas cleaning and pyrolysis stages, respectively. In the gas cleaning stage, the impact stems from electricity consumption in $CO_2$ liquefaction and natural gas used until the synthesis gas is utilized, whereas in the pyrolysis stage, the significant effect in this impact category arises from the natural gas used during startup and electricity consumption for biomass pretreatment.

Literature on LCA studies of biomass pyrolysis also highlights MAETP results as a significant impact category. Differences in MAETP results can vary depending on factors such as the type of biomass used, details of the pyrolysis process, and energy consumption (Elfallah Saad et al., 2024; Ferdoush et al., 2024; Heidari et al., 2019).

*4.1.1.2.* Global warming potential. Global Warming Potential (GWP) is a significant indicator used in LCA to measure the impact of greenhouse gas emissions associated with a product or process, quantified in carbon dioxide equivalents ($CO_2$-eq) units (Liu et al., 2023).

GWP compares the warming potential of greenhouse gases over a specific time horizon, helping assess the contribution of various activities to global warming. In the context of LCA, GWP serves as a crucial metric for understanding and reducing the environmental footprint of different systems and facilities, guiding efforts towards sustainable and greener solutions (Sphera Solutions GmbH et al., 2020).

Figure 4.2 displays scenario-based results of the GWP impact category.

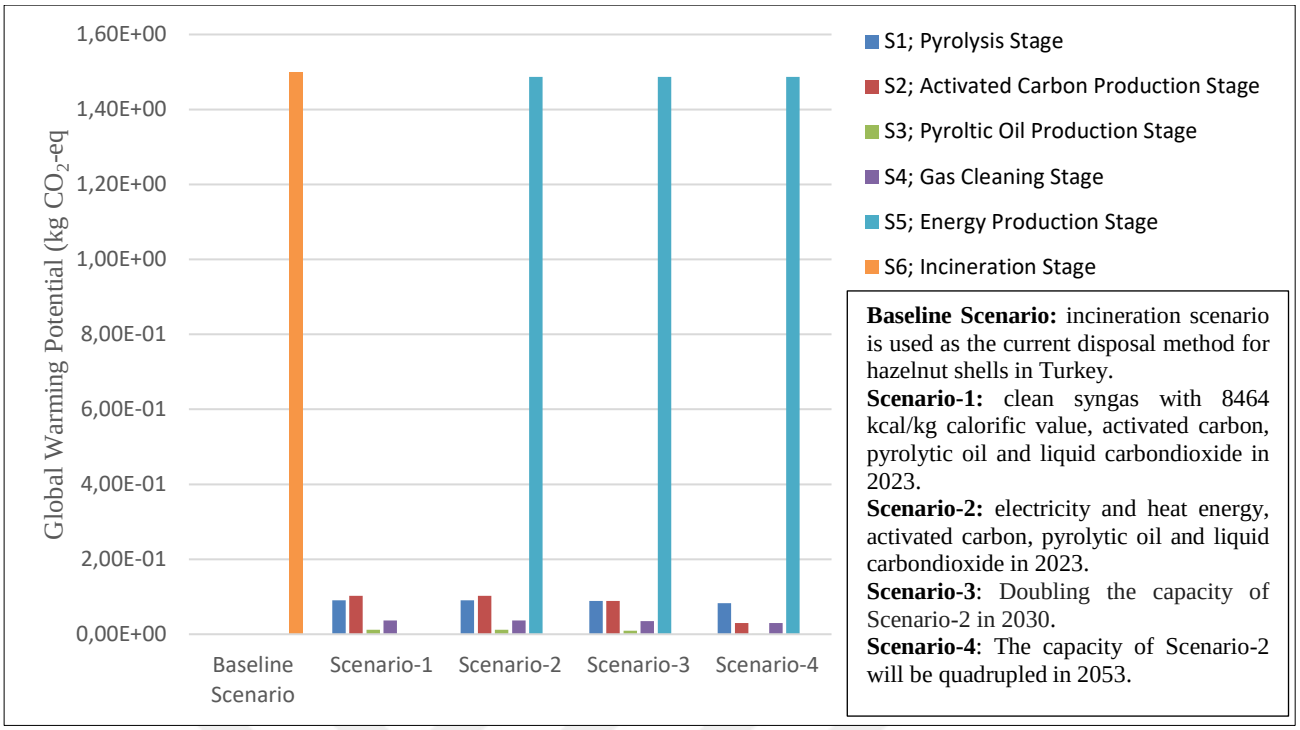


Figure 4.2. Quantified Global Warming Potential.

Based on the LCA results, Global Warming Potential (GWP) emerges as another essential impact category. The baseline scenario reflects the current state in Turkey, where hazelnut shells are incinerated; thus, it is considered the baseline scenario. Scenario 1 describes a situation where high-calorific-value syngas obtained from the pyrolysis of biomass waste is used for various purposes (as outlined in section 2.2.2.1). In other scenarios, a cogeneration unit has been added to generate electricity and thermal energy from this syngas.

While the baseline scenario only provides energy recovery, the plant scenario allows for the recovery of a high-calorific-value energy, along with significant quantities of activated carbon and other valuable by-products, thereby obtaining substantial economic value from biomass. The baseline scenario generates 83.8% higher GWP than Scenario 1, in which the recovered energy is directly used without converting it to electricity and heat.

Although the base scenario has 13.3% less GWP than Scenario 2, where the cogeneration unit is added, the biomass potential is evaluated by obtaining various valuable by-products that have economic value as well as energy in Scenario 2. This approach enables the biomass energy potential to be utilized more efficiently.

In the pyrolysis plant scenarios, it has been calculated that adding a cogeneration unit (S5) increases the GWP by 1.49 kg $CO_2$-equivalent compared to Scenario 1. This is due to $NO_x$ and $CO_2$ emissions resulting from the combustion of syngas mixed with air in this unit.

Findings indicate that another major source of GWP is the activated carbon production process (S2). This is due to $CO_2$ emissions from the high electricity consumption of nitrogen generators and natural gas consumption during the startup period, as well as the facility's use of syngas. The study also examined the effects of using the syngas produced in the facility. It was observed that using clean syngas to meet the energy needs in the system created an approximately 8% positive impact on the GWP value.

The pyrolysis stage (S2) includes the transport of biomass to the facility, pre-treatment of the biomass, and pyrolysis processes; diesel consumption, electricity, natural gas, and syngas consumption at these stages contribute to GWP. The gas cleaning (S4) and pyrolytic oil production (S3) stages make the fourth and fifth most significant contributions to this impact category due to energy consumption. The study assumed an industrial symbiosis scenario in which the facility is located in an organized industrial zone near the raw material source. Therefore, low transportation distances do not significantly contribute to GWP.

Furthermore, in the 2030 and 2053 scenarios, as the share of renewable energy sources such as wind, solar, and hydropower increases in electricity generation, the share of fossil fuels, particularly coal and natural gas, in electricity generation decreases. Fossil fuels are a significant contributor to CO2 emissions and other pollutants. The increase of renewable energy in the electricity projections leads to a decrease in GWP. As a result, GWP decreases by 1.16% in Scenario 3 and by 5.78% in Scenario 4 compared to Scenario 2.

The most well-known impact value in LCA studies on biomass pyrolysis is GWP. However, as mentioned in the 2.2.3. section, the GWP value in LCA studies conducted in this field has a wide range as it is affected by how the designed systems operate (such as temperature, heating rate, raw materials used), LCA boundaries, and the LCA model used. Additionally, the processing of by-products in LCA is also a controversial issue. The system extension provides credit for avoided items and thus changes the GWP. For example, the GWP value is different if biochar is used for various purposes in system expansion (Yu et al., 2022).

*4.1.1.3.* Abiotic depletion potential. Abiotic Depletion Potential (ADP) is an environmental impact category that measures the risk of depletion of natural resources. ADP assesses the depletion of energy and mineral resources, aiming to determine the environmental impacts of their usage. Expressed in MJ (megajoules), ADP calculates the environmental effect of depleting a specific resource based on its energy equivalent (van Oers & Guinée, 2016).

Figure 4.3 illustrates the scenario-specific outcomes for the Abiotic Depletion Potential (ADP) impact category.

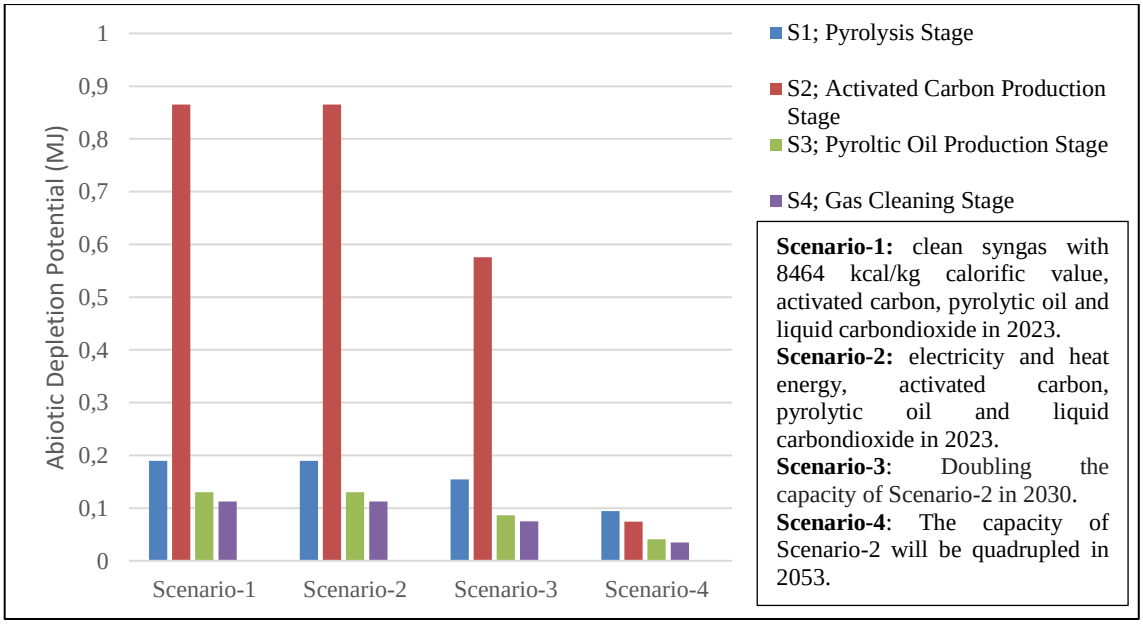


Figure 4.3. Quantified Abiotic Depletion Potential.

According to the LCA results, ADP is the third most significant impact category. When analyzing the results, it is evident that the largest contributions to ADP, in all scenarios except Scenario 4, come from the activated carbon production and pyrolysis steps. The primary chemical groups causing abiotic depletion potential are mostly associated with hydrocarbons released during the depletion of fossil fuels, so the primary reason for this is the high electricity consumption and natural gas consumption during the start-up period (3 hours) in these processes.

Increasing the share of renewable energy in electricity projections and the goal of eliminating fossil fuel use by 2053 significantly contribute to reducing ADP in Scenario 3 and Scenario 4. The energy usage in the pyrolytic oil production stage relies solely on electricity, which is directly influenced by this projection and helps achieve the lowest ADP among the steps. Additionally, the

results show that the cogeneration unit does not impact the abiotic depletion potential since it uses biomass-based synthesis gas as fuel.

The plant's reuse of synthesis gas produced during pyrolysis to meet its energy needs at various points also contributes to the low impact level of ADP. To calculate the effect of using the synthesis gas produced by the plant on ADP in the system, the situation where the plant uses natural gas instead of synthesis gas was also run over GaBi 8.0. It was observed that using the synthesis gas produced by the plant provided a 36% improvement in the ADP category. Using synthesis gas for energy production reduces fossil fuel consumption and increases the overall efficiency of the process. This approach minimizes the plant's environmental impact, promoting a sustainable production process.

In conclusion, increasing renewable energy sources and minimizing fossil fuel usage are critical in reducing ADP values. In addition to these effects, the plant's production of electricity and heat from biomass will also positively affect ADP by reducing fossil fuel consumption and the depletion of limited natural resources. In addition, obtaining activated carbon from biochar has the potential to provide positive effects on ADP as it will provide an alternative to fossil resources traditionally used in active carbon production.

*4.1.1.4.* Human toxicity potential. Human Toxicity Potential (HTP) is a metric that evaluates the potential harmful effects of specific chemical substances on human health. HTP is used to calculate the toxic impacts on human health following the release of chemicals into the environment, typically expressed in kilograms of Dichlorobenzene equivalent (kg DCB eq.) (McKone & Hertwich, 2001).

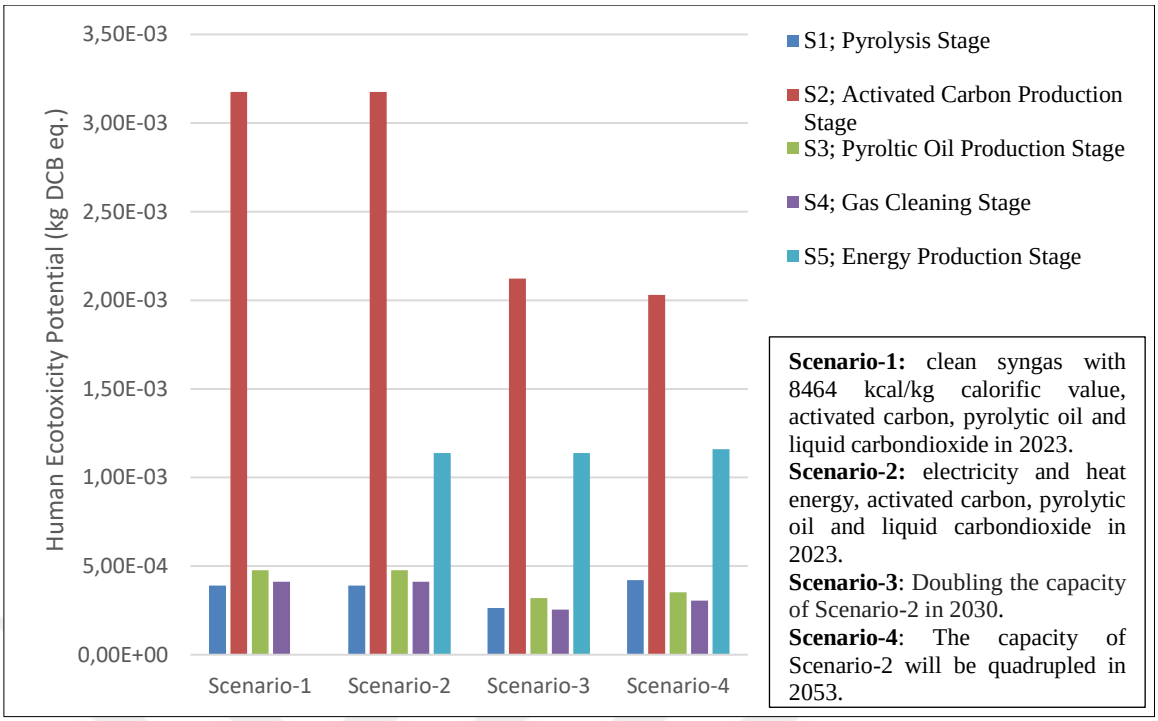


Figure 4.4. Quantified Human Toxicity Potential.

The results of these LCA studies show that the human toxicity potential for the designed pyrolysis plant ranges between 0.0041 and 0.0056 kg DCB. The plant primarily meets its energy needs with electricity and its produced syngas. Changes in the electricity mix in 2030 and 2053 indicate that the plant's impact in this category could decrease over the years.

When comparing Scenario 1 and Scenario 2, it is observed that in the same base year, the final product being clean syngas in Scenario 1 contributes 24.4% less to the energy produced by the plant compared to Scenario 2, where the syngas is returned to the electricity and heat production plant. When examining the impact of the production stages in this category, it is seen that they are ranked as S2 > S3 > S4 > S1 > S5. When reviewing literature results, it is found that LCA studies on biomass pyrolysis mainly evaluate 2 or 3 impact categories; thus, the evaluation of human toxicity potential is limited. In systems that evaluate this impact category, it is observed that similar results are reached due to electricity consumption, which is in line with the results discussed in this study, and that activated carbon production has the highest impact in this category (Heidari et al., 2019; Yu et al., 2022).

## 4.2. Normalization

Normalization is the process of dividing indicator values by a reference value to make environmental consequences comparable to a given reference value (a particular place, time period,

etc.). Through this technique, various environmental consequences may be combined and their relative relevance in the total environmental burden can be understood. Normalization results are unitless, which allows for comparison between impact categories. The normalization step, which enables a better understanding of the relative magnitude of indicator results, is not a mandatory step in the LCA methodology. In the normalization phase of this LCA study, the CML2001 – January 2016, World, year 2000 option was used. Figure *4.5* the percentage of impact categories for each scenario.

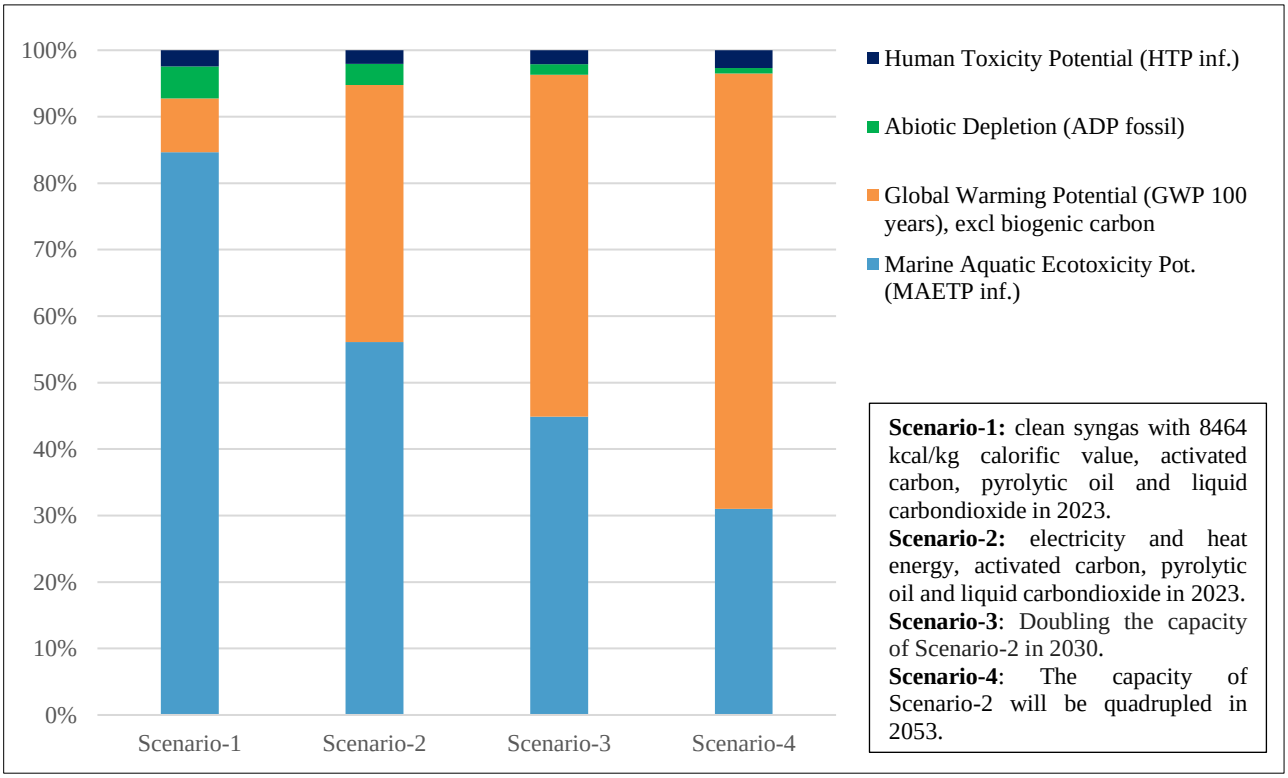


Figure 4.5. Scenario Based Normalization Results.

When examining the normalization results, it is observed that MAETP has the largest impact in Scenario 1 and Scenario 2. However, in Scenarios 3 and 4, where the share of renewable energy in the electricity mix is increased, this impact becomes the second largest. It is noted that in scenarios featuring cogeneration units, GWP impact caused by exhaust emissions has become the largest impact category in Scenario 3 and Scenario 4. While the highest normalization result in the ADP category is seen in Scenario-1 and Scenario-2 due to fossil fuels in the electricity mix of 2023, similar results are seen in all scenarios in the HTP category.

The analysis of the normalization findings reveals that, due to the existing energy generation mix, the MAETP effect category has the most significant influence across all scenarios. The GWP

percentages in each scenario are 8%, 39%, 45%, and 31%, but the MAETP percentages are 85%, 56%, 51%, and 65%. When the ADP percentages are examined in the normalization results, it is seen that they change as 5%, 3%, 2%, and 1%, respectively, and the changing energy projections contribute to the gradual decrease of the rate of this impact category. With the gradual decline of the ADP rate, the normalization values of HTP are seen as 2% in Scenario 1 and Scenario 2, while it is 3% in Scenario 3 and Scenario 4.

# 5. CONCLUSION AND RECOMMENDATION

The aim of this thesis is to conduct a life cycle assessment of a pyrolysis plant scenario that enables the production of renewable energy and value-added products by contributing to the circular bioeconomy of biomass in line with the EU green deal and bioeconomy strategy. The study aims to identify environmental hotspots of such facilities that contribute to the valorization of waste, more efficient use of resources, and circular bioeconomy. It also emphasizes the system's contributions to the alignment with the European Union bioeconomy strategy and the Green Deal targets by considering the base case scenario of incineration, which is the current disposal method of the studied biomass waste in Turkey. It also provides insights into how the widespread adoption of such facilities changes according to the target years and the effects of using energy in different ways. In this study, ISO 14044 LCA methodology was applied, and the CML2001 – Jan. 2016 LCIA methodology was evaluated based on four different impact categories: marine aquatic ecotoxicity potential, global warming potential, abiotic depletion potential, and human toxicity potential. Furthermore, the normalization results, which are an optional phase of the LCA methodology, were examined in this study. The environmental impacts of the plant were analyzed in five steps, considering the obtained products: pyrolysis step, activated carbon production process, pyrolytic oil extraction step, gas cleaning step, and energy production step, based on scenarios.

In this study, the baseline scenario examines the burning of hazelnut shells, drawing attention to the current situation in Turkey. Scenario 2 evaluates the base year (2023) scenario, which includes electricity and heat energy production, while Scenario 3 and Scenario 4 show the consequences of changes in electricity projections, drawing attention to the potential increase in the production capacity of such facilities thanks to the raw material potential. Scenario 1 examines the scenario where clean synthesis gas is used directly as energy in other facilities as an alternative to electricity and heat production.

In the current situation, while burning biomass results in a higher GWP compared to the pyrolysis plant scenario where the final product is raw energy, it can provide an energy gain with a much lower calorific value than the energy obtained by pyrolysis alone. The utilization of biomass waste in such facilities can provide economic and environmental added value with high calorific value energy output, a high amount of active carbon production, and other by-products. This demonstrates the contribution of such facilities to EU targets and strategies.

The results show that Scenario 1 has a much lower GWP value than the scenarios where this synthesis gas is converted into electricity and heat energy with the addition of a cogeneration unit. In scenarios involving electricity and heat energy production, it was observed that the GWP is mainly due to emissions from exhaust gases released from the combustion of the synthesis gas-air mixture in the cogeneration unit.

The results demonstrate that MAETP is a significant environmental hotspot for such facilities due to emissions from electricity and natural gas. In Scenario-3 and Scenario-4, the electricity projections of the facility, which contribute significantly to this impact category, were evaluated for the years 2030 and 2053, and it is seen that the impact can be reduced by 39% and 69%, respectively, compared to Scenario 2, thanks to the changed electricity projections. This result shows that such facilities can be viable options contributing to the circular bioeconomy in line with the 2030 and 2053 targets.

Similarly, the ADP is mainly due to the plant's electricity consumption, and the projections in Scenario 3 and Scenario 4 showed that the abiotic depletion potential is reduced by 31% and 81%, respectively, compared to Scenario 2. In addition, the obtained activated carbon and other valuable by-products can help lessen the abiotic depletion potential by replacing fossil-based products in industrial applications. HTP is the category with the most minor impact and can be considered negligible compared to other categories.

When the normalization results are evaluated, it is seen that the MAETP impact category has the highest impact in all scenarios due to the current electricity generation mix. The percentage of MAETP is 85%, 56%, 51% and 65% in the scenarios, respectively, while the percentage of GWP is 8%, 39%, 45% and 31%, respectively. The ADP and HTP categories are effective at similar rates in all scenarios, and their impacts appear low.

In this study, an environmental assessment of a pyrolysis plant using hazelnut shell and apricot kernel waste as raw material was conducted. The study provides a comparison opportunity for future studies with different biomass inputs or pyrolysis systems. The results obtained significantly contribute to literature and guide the applied field. Sensitivity analysis, one of the voluntary stages of LCA, was not performed within the scope of this study. Information on the factors that may affect the quality of the results has been provided, and in future studies in this field, sensitivity analysis can be performed in the LCA of such facility scenarios, and more detailed information can be obtained

about the consistency of the findings by showing how the LCA results respond to certain variables. In addition, this study can be compared with scenarios where captured $CO_2$ is re-fed to the system and where active carbon production is carried out with different methods, and optimizations can be made in such facilities can be examined.

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# APPENDIX A: INVENTORY DATA

Table A.1. Detailed Inventory Data of the Study – Input Values.

| Stages | LCA Phase | Processes | Input** | Unit | Quantity |
|---|---|---|---|---|---|
| S1; Pyrolysis Stage | Raw material extraction | Transportation | Diesel Consumption | lt/km | 3.2 |
| | Manufacturing | Biomass Pretreatment (Crushing) | Electricity Consumption | kWh | 60 |
| | | Pyrolysis | Mixed Feedstock | kg | 3000 |
| | | | Natural Gas Consumption | $Nm^3$ (for 3 hour) | 130 |
| | | | Clean Syngas Consumption | kg | 117 |
| S2; Active Carbon Production Stage | Use: Product and Obligatory Product Utilization | Carbonization Unit | Biochar Amount | kg | 570 |
| | | | Nitrogen | $m^3$ | 2400 |
| | | | Clean Syngas Consumption | kg | 40 |
| | | Biochar Storage | Biochar Amount | kg | 570 |
| | | Nitrogen Generator | Air Consumption | $m^3$ | 3077 |
| | | | Electricity Consumption | kWh | 500 |
| S3; Pyrolytic Oil Production Stage | | Cooling Unit | Pyrolytic Liquid Amount | kg | 360 |
| | | | Electricity Consumption | kWh | 50 kWh |
| | | | Clean Syngas Consumption | kg | 45 |

Table A.2. Detailed Inventory Data of the Study – Input Values (continued).

| Stages | LCA Phase | Processes | Input** | Unit | Quantity |
|---|---|---|---|---|---|
| S3; Pyrolytic Oil Production Stage | Use: Product and Obligatory Product Utilization | Two Phase Separator | Pyrolytic Liquid Amount | kg | 360 |
| | | | Electricity Consumption | kWh | 30 |
| S4; Gas Cleaning Stage | | Amin Scrubbing & Amine Regeneration Unit | Methyl ethyl amine amount | kg | 1.3 |
| | | | Water | kg | 7.4 |
| | | | Amount of Syngas | kg | 2070 |
| | | | Clean Syngas Consumption | kg | 45 |
| | | $CO_2$ Liquefaction | Amount of Captured $CO_2$ | kg | 569 |
| | | | Electricity Consumption | kWh / kg$CO_2$ | 110 |
| S5*; Electricity and Heat Production Stage | | Cogeneration Unit | Amount of Clean Syngas | kg | 1299 |
| - | End of Life Phase | Wastewater Treatment | Wastewater Amount | kg | 324 |
| | | | Electricity Consumption | kWh | 6 |

Table A.3. Detailed Inventory Data of the Study – Output Values.

| Stages | LCA Phase | Processes | Output** | Unit | Quantity |
|---|---|---|---|---|---|
| S1; Pyrolysis Stage | Raw material extraction | Transportation | - | - | - |
| | Manufacturing | Biomass Pretreatment (Crushing) | Mixed Feedstock | kg/hr | 3000 |
| | | Pyrolysis | Syngas | kg/hr | 2070 |
| | | | Liquid | kg/hr | 360 |
| | | | Biochar | kg/hr | 570 |
| S2; Active Carbon Production Stage | Use: Product and Obligatory Product Utilization | Carbonization Unit | Activated Carbon | kg/hr | 456 |
| S3; Pyrolytic Oil Production Stage | | Cooling Unit | Pyrolytic Liquid | kg | 360 |
| | | Two Phase Separator | Pyrolytic Oil | kg | 36 |
| | | | Wastewater | kWh | 314 |
| S4; Gas Cleaning Stage | | Amin Scrubbing & Amine Regeneration Unit | $CO_2$ gas | kg/hr | 569 |
| | | | Clean syngas | kg/hr | 1350 |
| | | $CO_2$ Liquefaction | Liquid $CO_2$ | kg/hr | 569 |
| S5*; Electricity and Heat Production Stage | | Cogeneration Unit | Electriciy | MW | 2 |
| | | | Heat | MW | 2 |
| - | End of Life Phase | Wastewater Treatment | Treated wastewater | kg/hr | 324 |

Note: Quantities only include information about the input data.
*Electricity and heat production phase is not included in Scenario 1.
** These inventory data entries include Scenario 1 and Scenario 2 data only. In Scenario 3, all data were doubled, and 2030 Türkiye's electricity mix was considered. In Scenario 4, all data increases linearly, and Turkey's 2053 electricity mix projections are considered for electricity consumption.

# APPENDIX B: ULTIMATE AND PROXIMATE ANALYSIS OF FEEDSTOCKS

Hazelnut shells and apricot kernels are highly effective biomass raw materials for pyrolysis. Low ash content significantly advantages over biomass such as rice straw, rice hulls, and coffee pulp. This feature reduces reactor blockage and equipment wear during pyrolysis, providing a more efficient operation. Their fixed carbon ratio gives hazelnut shells and apricot kernels sufficient carbon sources for biochar production. In addition, its 70-80% volatile matter content supports the production of gas and liquid products during pyrolysis, providing high efficiency. While biomass with high volatile matter content, such as sugar cane bagasse and corn cob, is limited to excess gas production, the balanced structure of hazelnut shell allows gas, liquid, and solid products to be obtained in ideal proportions. These features make hazelnut shell and apricot kernel a more effective option than other biomass types regarding energy production and obtaining high-value products. The future importance of using hazelnut shells in pyrolysis processes in Turkey has great potential. Since Turkey is a significant global hazelnut producer, especially in the Black Sea region, a lot of hazelnut shell waste is generated annually. Valuable products such as activated carbon, liquid fuels, and gases obtained from the pyrolysis of hazelnut shells create added economic value and allow for an increase in domestic production. The low ash and high volatile matter content of hazelnut shells provide efficient energy production in the pyrolysis process, which helps Turkey increase its renewable energy resources.

Table B.1. Proximate Analysis for Different Biomass Types (Maguyon-Detras et al., 2019).

| | **Ash (% wt)** | **Volatiles (% wt)** | **Fixed Carbon (% wt)** |
|---|---|---|---|
| Rice straw | 14.11–22.70 | 60.55–78.07 | 6.93–16.75 |
| Rice husks | 15.14 | 73.41 | 11,44 |
| Corn cob | 2.3 | 91.16 | 6.54 |
| Wheat straw | 6.63 | 83.08 | 10.29 |
| Coffee hulls | 11.5 | 77.5 | 11 |
| Bamboo leaves | 11 | 70.3 | 18.7 |

Table B.1. Proximate Analysis for Different Biomass Types (Maguyon-Detras et al., 2019) (continued).

| | **Ash (% wt)** | **Volatiles (% wt)** | **Fixed Carbon (% wt)** |
|---|---|---|---|
| Sugarcane bagasse | 8.8 | 87 | 4.2 |
| Sugarcane peel | 12.6 | 77.3 | 10.1 |

Table B.2 and Table B.3 demonstrate the laboratory results of studied feedstocks.

Table B.2. Ultimate Analysis of Studied Feedstocks (Okutan, 2022)

| **Ultimate Analysis (w/w%)** | **Hazelnut Shell** | **Apricot Kernel** |
|---|---|---|
| C | 45.50 | 45.25 |
| H | 6.32 | 6.30 |
| N | 0.29 | 0.13 |
| S | 0.07 | 0.24 |
| O | 46.65 | 46.53 |

Table B.3. Proximate Analysis of Studied Feedstocks (Okutan, 2022)

| **Biomass** | **Moisture (%)** | **Volatile Matter (%)** | **Ash (%)** | **Fixed Carbon (%)** | **Calorific Value** |
|---|---|---|---|---|---|
| Hazelnut Shell | 11.72 | 66.17 | 0.98 | 21.12 | 4370 |
| | - | 74.95 | 1.11 | 23.94 | |
| Apricot Kernel | 10.03 | 70.6 | 0.78 | 18.58 | 4310 |
| | - | 78.47 | 0.87 | 20.68 | |

# APPENDIX C: IMPORTANCE OF CML METHODOLOGY

The CML method is one of the popular methods used in life cycle impact assessment (LCIA). The detailed map for CML methodology is given in Figure C.1. Some points that distinguish CML from other LCIA methods are detailed below (Bałdowska-Witos et al., 2021).

- Midpoint Approach: The CML methodology can address environmental impacts in more specific categories, such as global warming potential, acidification potential, and acidification potential. The midpoint approach contains less uncertainty in the cause-effect relationships of impact categories. This allows more specific focuses to be determined than endpoint methods such as ReCiPe. For example, if greenhouse gas emissions (GWP) or toxicity effects must be examined separately, the CML method is ideal.

- Categorical Impact Areas: The CML method focuses on ten impact categories. These categories provide detailed analysis and a better understanding of specific environmental impacts.

- Scientific Validity and Prevalence: CML is primarily designed to analyze global impacts, differentiating it from regionally focused methods such as TRACI. In addition, the CML method is scientifically well-documented and frequently updated. For this reason, it is widely preferred in academic studies. It is compatible with ISO 14040 and ISO 14044 standards.

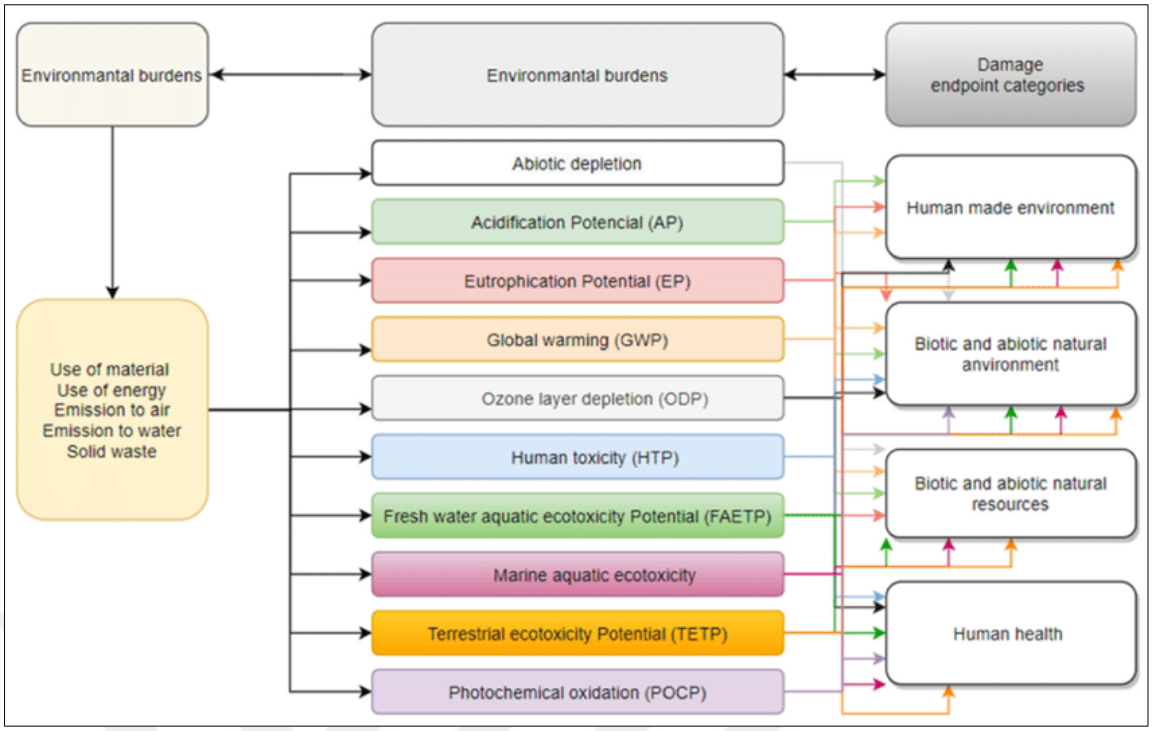


Figure C.1. Detailed Map for CML Methodology (Bałdowska-Witos et al., 2021)

# APPENDIX D: METHODOLOGY FOR IMPACT CATEGORIES

The environmental impacts of life cycle inventory results for systems are assessed using LCIA. In the context of Life Cycle Impact Assessment (LCIA), it is crucial to understand the chemical components and factors that contribute to various environmental impacts. Each impact category represents a different aspect of environmental sustainability, and the substances involved can significantly affect ecosystems and human health. Below table overviews the chemical components and their impact factors associated with different LCIA impact categories.

LCIA is a key step in the LCA process which evaluates the environmental impacts of a product or process. It involves several elements that help quantify and interpret the potential effects of various environmental stressors. The elements of LCIA are classification, characterization, normalization, and weighting. The first step, classification, involves assigning each inventory parameter to the relevant impact category. This step determines which categories the environmental impacts will be included in. The second step, characterization, quantifies the impact of each inventory parameter on a specific impact category. In this step, the contribution of each parameter to the impact category is calculated using a characterization factor. Finally, the inventory step is the stage where all data on the life cycle of the product system are collected and organized systematically. These data form the basis for the assessment of environmental impacts. Classification, characterization and inventory steps are complementary processes for LCA to comprehensively calculate environmental impacts (Lee & Inaba, 2004).

## Global Warming Potential (GWP)

GWP measures greenhouse gases' potential to disrupt the atmosphere's energy balance. This effect is due to the ability of gases to absorb and re-emit infrared radiation. GWP is usually assessed over a time horizon of 100 years, and the unit is carbon dioxide equivalent (kg $CO_2$ eq.). GWP of a gas is a ratio of how much warming a given amount of the gas causes compared to the same amount of carbon dioxide.

$$Global\ Warming\ Potential = \sum_i GWP_{a,i}\ x\ m_i \qquad \text{Eq. 1}$$

where:

$GWP_{a,i}$ is the Global Warming Potential for substance *i* integrated over a years

$m_i$ (kg) is the quantity of substance *i* emitted.

Greenhouse gases (GHGs) contribute to the warming of the Earth by absorbing energy and reducing the rate at which this energy escapes into space, functioning like an insulating blanket. Different GHGs vary in their impact on warming due to differences in their energy absorption capacity, known as "radiative efficiency," and atmospheric lifetime.

Since 1990, the Intergovernmental Panel on Climate Change (IPCC) has used the Global Warming Potential (GWP) metric to compare the warming effects of various gases. GWP measures the energy absorbed by the emission of 1 ton of a gas over a specific period, relative to 1 ton of carbon dioxide ($CO_2$). The standard time frame for GWPs is 100 years. This metric offers a unified way to aggregate emissions of different gases and aids policymakers in evaluating emissions reduction strategies across sectors and gas types.

Carbon dioxide ($CO_2$), the baseline reference gas, has a GWP of 1 regardless of the time period. $CO_2$ emissions have a long-lasting impact, with atmospheric concentrations persisting for thousands of years. Methane ($CH_4$), by contrast, has a GWP of 27–30 over 100 years. Although $CH_4$ remains in the atmosphere for a shorter period—about a decade—it absorbs significantly more energy than $CO_2$, which offsets its shorter lifetime. $CH_4$'s GWP also considers indirect effects, such as its role as a precursor to ozone, another greenhouse gas.

Nitrous oxide ($N_2O$) has a GWP that is 273 times greater than that of $CO_2$ over a 100-year period and remains in the atmosphere for more than 100 years. Synthetic gases such as chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), hydrochlorofluorocarbons (HCFCs), perfluorocarbons (PFCs), and sulfur hexafluoride ($SF_6$) are classified as high-GWP gases due to their ability to retain substantially more heat per unit mass compared to $CO_2$. The GWPs of these gases can range into the thousands or even tens of thousands. In this thesis, the leading gases affecting the global warming potential are nitrous oxides and $CO_2$. While $CO_2$ is released, especially during meeting the facility's energy needs (natural gas, synthesis gas consumption), nitrous oxides are released in the cogeneration unit where electricity and heat energy production is carried out. In electricity, the GWP contribution comes mainly from $CO_2$ emissions from the combustion of fossil fuels. In addition, greenhouse gases such as methane $CH_4$ and $N_2O$ are also released during coal mining, natural gas production, and combustion processes, contributing to the GWP. The high share of fossil fuels increases the total emissions of these gases and their impact on the GWP.

Table D.1. IPCC Global Warming Potential (GWP) values relative to $CO_2$ (Intergovernmental Panel on Climate Change, 2024)

| Common chemical name or industrial designation | Chemical formula | GWP values for 100-year time horizon | | |
|---|---|---|---|---|
| | | Fourth Assessment Report (AR4) | Fifth Assessment Report (AR5) | Sixth Assessment Report (AR6) |
| **Major Greenhouse Gases** | | | | |
| Carbon dioxide | $CO_2$ | 1 | 1 | 1 |
| Methane – non-fossil | $CH_4$ | 25 | 28 | 27.0 |
| Methane – fossil | $CH_4$ | N/A | 30 | 29.8 |
| Nitrous oxide | $N_2O$ | 298 | 265 | 273 |
| Nitrogen trifluoride | $NF_3$ | 17,200 | 16,100 | 17,400 |
| Sulfur hexafluoride | $SF_6$ | 22,800 | 23,500 | 24,300 |

In evaluating the impacts of climate change, the global warming potential (GWP) serves as a key indicator, quantifying the effects of various greenhouse gases in terms of carbon dioxide equivalent ($CO_2$ eq.). In this context, five distinct GWP indicators are calculated: GWP-fossil, which reflects the emissions from fossil fuel combustion; GWP-biogenic, which accounts for biogenic emissions; and GWP-land use and land use change, which considers emissions resulting from land use and land use changes. The GWP-total is the sum of these three indicators, while GWP-GHG is determined assuming that the characterization factor for biogenic $CO_2$ is zero. These calculations are made over a 100-year period (GWP100). According to the IPCC report, gases such as methane ($CH_4$) and nitrous oxide ($N_2O$) have significantly higher GWP values than carbon dioxide, with methane having a value of 25 kg $CO_2$ equivalent and nitrous oxide at 298 kg $CO_2$ equivalent. Such assessments are crucial for understanding the potential impact of greenhouse gases on global warming and for shaping climate change mitigation strategies.

## Marine Aquatic Toxicity Potential

Marine Aquatic Toxicity Potential (MAETP) is an environmental impact indicator to assess toxic effects on marine aquatic ecosystems. MAETP calculates the potential damage to marine ecosystems caused by a specific activity or process. This calculation provides a metric that models the effects of substances that may harm the ecosystem, especially aquatic toxic chemicals, in the marine environment. The main elements used in calculating MAETP include the solubility of chemicals in the aquatic environment, their biological effects, and toxicity data.

This concept, which provides information about the general toxic effects of a group of substances or processes rather than a specific chemical, is calculated in terms of 1,4-Dichlorobenzene eq.

$$Marine\ Aquatic\ Ecotoxicity\ Potential = \sum_i \sum_{ecom} MAETP_{ecom,i}\ x\ m_{ecom,i} \qquad \text{Eq. 2}$$

Where:

$MAETP_{ecom,i}$ is the characterization factor for substance *i* emitted to emission compartment seawater

$m_{ecom,i}$ is the emission of substance *i* to medium seawater.

When LCA studies involving MAETP are examined, it is observed that electricity dominates with a contribution exceeding 90% to MAETP. The analysis of the substances mainly responsible clearly shows that non-ferrous metals are indeed the only relevant substances (Hussain et al., 2013). Depending on the electricity production mix, Marine Aquatic Ecotoxicity Potential (MAETP) is caused by components released during energy production that have toxic effects on the marine ecosystem. Heavy metals such as mercury (Hg), lead (Pb), and cadmium (Cd) released by the combustion of fossil fuels reach the water systems and cause serious toxic effects on marine organisms. In addition, gases such as sulfur oxides ($SO_x$) and nitrogen oxides ($NO_x$) can disrupt the chemistry of seawater by forming acidic compounds and damage the ecosystem. Organic pollutants such as polyaromatic hydrocarbons (PAHs) resulting from fossil fuel combustion also cause long-term toxic effects on the marine ecosystem. While the high share of fossil fuels in electricity production increases the emission of these components, the widespread use of renewable energy sources can significantly reduce the effects on the MAETP.

Table D.2. Primary Substance Contributing to MAETP (Hussain et al., 2013)

| No | Substance | Initial Compartment | Amount (kg 1,4-DB eq) | Cumulative contribution |
|---|---|---|---|---|
| | Total of all compartments | - | 1.31E+11 | 100% |
| 1 | Se | Water | 3.57E+10 | 27% |
| 2 | Ni | Water | 3.47E+10 | 27% |
| 3 | Ba | Water | 2.07E+10 | 16% |
| 4 | V | Air | 1.27E+10 | 10% |
| 5 | V | Water | 1.24E+10 | 9% |
| 6 | Cu | Water | 5.15E+09 | 4% |
| 7 | Co | Water | 2.51E+09 | 2% |
| 8 | Mo | Water | 1.61E+09 | 1% |
| 9 | Zn | Water | 1.56E+09 | 1% |
| 10 | Ni | Air | 1.09E+09 | 1% |
| 11 | Se | Air | 9.79E+08 | 1% |
| | Above substances | - | **2.60 E+11** | **99%** |

**Human Toxicity Potential**

The Human Toxicity Potential (HTP) is a toxic equivalence potential that quantifies the potential harm of a unit of a chemical released into the environment. The HTP considers both natural toxicity and source-dose relationships when assessing pollutant emissions. The Human Toxicity Potential (HTP) uses an exposure margin ratio to assess the health effects of exposure to carcinogenic and non-carcinogenic hazards. This potential takes into account the effects of chemicals and pollutants, typically considering both chronic and acute toxicity (McKone & Hertwich, 2001). The Human Toxicity Potential (HTP) associated with the electricity production mix arises from substances released during energy generation that have toxic effects on human health. Heavy metals such as mercury (Hg), arsenic (As), lead (Pb), and cadmium (Cd), emitted during the combustion of coal and other fossil fuels, spread into the air, water, and soil, causing significant toxic impacts on human health. Additionally, polycyclic aromatic hydrocarbons (PAHs), as organic compounds, exhibit carcinogenic and mutagenic effects, while nitrogen oxides ($NO_x$) and sulfur oxides ($SO_x$) contribute to air pollution, leading to respiratory diseases. Fine particulate matter (PM), released into the atmosphere through fossil fuel combustion, increases the risk of lung and cardiovascular diseases, and volatile organic compounds (VOCs) and other pollutants cause acute and chronic health effects. The high share of fossil fuels in electricity production significantly increases the release of these toxic components, raising the HTP. However, the widespread adoption of renewable energy sources could be crucial in mitigating these adverse impacts on human health.

The combination of environmental fate factor, human exposure factor, human toxicity effect factor, and toxicity-effect damage factor determines human toxicity. The fate factor describes how chemicals distribute and transform in the environment; the exposure factor relates the chemical mass in the environment to human exposure; the effect factor shows the potential human toxicity effects per unit of chemical exposure; and the damage factor links these effects to human health impacts (McKone & Hertwich, 2001). The cause-and-effect chain of toxicity-related damage to human health and ecosystem quality caused by chemical emissions is summarized in Figure D..

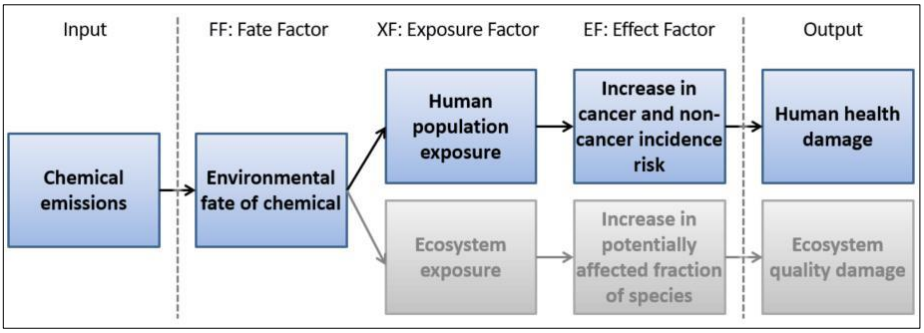


Figure D.3. Demonstration of cause-and-effect chain of human toxicity (*LCI - Human Toxicity*, n.d.)

The HTP is expressed in the unit of toxicity equivalents (TE), which is usually "kg 1.4-dichlorobenzene equivalents" (kg 1.4-DB eq.) or other standardized reference chemicals. The formulation of this impact category is:

$$Human\ Toxicity\ Potential = \sum_i \sum_{ecom} HTP_{ecom,i}\ x\ m_{ecom,i} \qquad \text{Eq.3}$$

Where:

$HTP_{ecom,i}$ is the characterization factor for substance *i* emitted to emission compartment.

$m_{ecom,i}$ is the emission of substance *i* to medium.

**Abiotic Depletion Potential**

Abiotic Depletion Potential (ADP) is an impact category used in life cycle assessments (LCA) to measure the potential for depletion of abiotic (non-living) resources. ADP is based on the depletion of natural resources, i.e., the reduction of available reserves of mineral and fossil resources extracted from the Earth's crust. The unit of ADP is kg Sb-eq (Antimony Equivalent) and measures the contribution of each mineral or fossil resource consumed during a product or process to depletion. The global depletion potential of a resource is calculated by considering the amount extracted and the size of the resource's economically recoverable reserve. This method guides sustainable resource use strategies by analyzing the environmental impacts of resources consumed throughout the life cycle of products or processes.

ADP is based on the concept of ultimate reserves and considers the extraction of mineral resources as a depletion process that reduces geological stocks (Van Oers & Guinée, 2016). However, the data models used in LCI processes may lead to inconsistencies in the application of ADP. For example, calculating the total mass of target metals extracted from the Earth's crust by including the

parts transferred to landfills contradicts ADP. Because these metals may return to the Earth's crust at some point when landfill management ends, this does not contribute to the depletion of geological stocks. Therefore, to apply ADP consistently, only the minerals produced should be considered resource flows, and metals transferred to waste should be excluded. With these features, ADP is an essential tool that aims to reduce environmental impacts in resource management, energy efficiency, recycling, and alternative resource use (Van Oers & Guinée, 2016).

In a biomass pyrolysis facility, the Abiotic Depletion Potential (ADP) is primarily influenced by the consumption of fossil fuels and energy during various processes. Electricity consumption plays a significant role, particularly when the electricity is sourced from the 2023 electricity mix, which relies heavily on fossil fuels such as coal and natural gas. These non-renewable resources contribute directly to the depletion of abiotic resources. Additionally, the production of nitrogen gas, used in the activation process for producing activated carbon, further increases ADP due to its high energy demands, typically met by fossil-based electricity. Lastly, the transportation of biomass feedstock, which often involves diesel fuel consumption, also contributes to the depletion of fossil energy resources, emphasizing the importance of minimizing transportation distances in such systems.

In line with the general framework of Life Cycle Impact Assessment (LCIA), the impact category indicator result for "abiotic depletion" is determined by multiplying the Life Cycle Inventory (LCI) results, specifically the extraction amounts of elements and fossil fuels (measured in kg), with the characterization factors (ADPs expressed in kg antimony equivalents per kg of extraction). The reference substance selection is arbitrary and does not influence the relative magnitudes of the characterization factors. Antimony was chosen as the reference substance because it is the first element alphabetically for which a complete dataset, including extraction rates and ultimate reserves, is available. The results of these multiplications are then aggregated into a single score, yielding the indicator result in units of kg antimony equivalents (Van Oers & Guinée, 2016).

$$Abiotic\ Depletion = \sum_i Factor_i\ x\ m_i \qquad \text{Eq. 4}$$

$$Factor_i = \frac{EX_i}{molew_i} \qquad \text{Eq. 5}$$

Where:

$Factor_{,j}$ is the characterization factor for abiotic depletion of resource *i* based on the exergy content, while $m_i$(kg) is the quantity of resource *i* used,

$EX_i$ is the exergy content of one mole of resource *i*,

$molew_i$ the mole weight of resource *i*.

# APPENDIX E: NORMALIZATION

Normalization is achieved by dividing the characterization value of an impact category of a product system (characterized impact) by the normalization reference of the same impact category. The normalization value obtained as a result of this process (normalized impact) expresses the proportional contribution of the product system to an impact category in a specific geographical area and time period. This time period is defined in the normalization reference (Lee & Inaba, 2004).

The normalization reference is a different form of characterization. The main difference between the two is geographical and temporal system boundaries. While characterization covers only one product system, the normalization reference covers the entire region where the product system is located. The temporal boundary in the product system extends from the acquisition of raw materials to their ultimate disposal and usually covers a period longer than one year. On the other hand, the temporal boundary of the normalization reference is generally set at one year (Lee & Inaba, 2004).

The normalization reference (Ni) for an impact category (i) can be calculated similarly to the characterization value calculation method.

$$Ni, k = Loadk\ x\ eqvi, k \qquad \text{Eq. 6}$$

Where, Ni,k = the magnitude of characterized impact of the kth inventory parameter in the ith impact category, g x-eq/ yr,

Loadk = the quantity of the kth inventory parameter, g/yr,

eqvi,k = equivalency (characterization) factor of the kth inventory parameter in the ith impact category, g x-eq/g

By summing up all inventory parameters and $k^{th}$ parameters, the total environmental impact or normalization reference for the $i^{th}$ impact category is calculated, as illustrated in the equation.

$$Ni = \sum Ni, k = \sum Loadk\ x\ eqvi, k \qquad \text{Eq. 7}$$

Where, Ni= normalization reference of the $i^{th}$ impact category, g x-eq/yr

The normalization reference is typically expressed in terms of person equivalent (PE) to account for the environmental impacts across different geographical scales of impact categories. These scales are classified as global, regional, and local. For example, global warming, ozone layer depletion, and

abiotic resource depletion are global impacts. Acidification and eutrophication are considered regional impacts, while photochemical oxidant formation is classified as a local impact. The geographical boundaries for these scales are defined as follows: global impacts encompass the entire planet, regional impacts cover specific areas such as East Asia or Western Europe, and local impacts refer to individual countries, regions, or cities (Lee & Inaba, 2004).

The normalization reference based on person equivalent is calculated using the below equation:

$$Ni = \frac{\sum(Loadk\ x\ eqvi,k)}{population\ size\ of\ the\ geographical\ system\ boundary} \quad \text{Eq. 8}$$

Where:

$N_i$ = normalization reference for the ith impact category, expressed in g x-eq / (pe-yr)

pe-yr = person equivalent per year

The normalized impact, or normalization value, is then calculated using the equation below:

$$NI, i = \frac{CI,i}{Ni} \quad \text{Eq. 9}$$

Where:

$NI_{,i}$ = normalized impact for the $i^{th}$ impact category, in expressed in (pe-yr) / fu,

$CI_i$ = characterized impact for the $i^{th}$ impact category.