

LIFE CYCLE ASSESSMENT IN CASE OF PYROLYSIS OF PAPER AND PLASTIC WASTES

by

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This thesis represents not only an academic journey but also a deeply personal one. Venturing into a field different from my undergraduate studies was both challenging and rewarding. It allowed me to grow, not just as a researcher but also as an individual, and I am proud of what I have accomplished.

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ABSTRACT

LIFE CYCLE ASSESMENT IN CASE OF PYROLYSIS OF PAPER AND PLASTIC WASTES

Rapid economic development and industrialization, coupled with a growing global population, have led to an unprecedented surge in waste generation, threatening both environmental and human health. Conventional waste management techniques struggle to process cellulose- and polymer-based composite label wastes due to their intricate structures in recycling operations. However, pyrolysis—a thermochemical process—can convert such non-recyclable wastes into energy and valuable chemical products, aligning with the principles of the circular economy. Cellulose, predominantly carbon, plays a critical role in biofuel production, while polymers, such as polyolefins and polystyrene, yield high-calorific-value products like hydrocarbon oils and syngas. These outputs, including syngas, LNG, and pyrolytic oil serve as carbon-neutral energy alternatives to fossil fuels, enhancing energy security and sustainability in industrial applications. This study evaluates the pyrolysis of label waste (85% cellulose and 15% polymers) using life cycle assessment (LCA) methodology. Leveraging experimental data from ITU Synthetic Fuels and Chemicals Technology Center (ITU-SENTEK), alongside market research and literature, the environmental performance of pyrolysis was compared with incineration in two scenarios. The findings revealed elevated Marine Aquatic Ecotoxicity Potential in the current scenario due to high electricity consumption, whereas the alternative scenario showed increased Global Warming Potential due to surplus CO₂ emissions from gas engines. Despite these challenges, pyrolysis presents a sustainable solution for energy recovery from label waste, contributing to waste management policies and the transition to a circular economy. These insights underscore its potential to promote sustainability and reduce reliance on fossil fuels in line with circular economy.

ÖZET

KAĞIT VE PLASTİK ATIKLARIN PİROLİZİNDE YAŞAM DÖNGÜSÜ DEĞERLENDİRMESİ

Hızlı ekonomik gelişme ve sanayileşme, artan küresel nüfusla birleşerek atık üretiminde eşi benzeri görülmemiş bir artışa yol açmış, bu da hem çevre hem de insan sağlığı için tehdit oluşturmuştur. Geleneksel atık yönetim teknikleri, geri dönüşüm işlemlerindeki karmaşık yapıları nedeniyle selüloz ve polimer bazlı kompozit etiket atıklarını işlemekte zorlanmaktadır. Ancak, piroliz—bir termokimyasal süreç—bu tür geri dönüştürülemez atıkları enerjiye ve değerli kimyasal ürünlere dönüştürebilir, döngüsel ekonomi ilkeleriyle uyumlu hale getirir. Selüloz, ağırlıklı olarak karbon içeren, biyoyakıt üretiminde kritik bir rol oynarken, poliolefinler ve polistiren gibi polimerler, hidrokarbon yağları ve sentez gazı gibi yüksek kalorili değerli ürünler elde eder. Bu çıktılar, biyogaz, LNG ve pirolitik yağ dahil olmak üzere, fosil yakıtlar için karbon nötr enerji alternatifleri olarak hizmet eder, endüstriyel uygulamalarda enerji güvenliğini ve sürdürülebilirliği artırır. Bu çalışma, etiket atıklarının (%85 selüloz ve %15 polimer) yaşam döngüsü değerlendirmesi metodolojisi kullanılarak pirolizini değerlendirmektedir. ITU Sentetik Yakıtlar ve Kimyasallar Teknoloji Merkezi (ITU-SENTEK) deneysel verilerini, piyasa araştırması ve literatürle birleştirerek, pirolizinin çevresel performansı iki senaryoda yakma ile karşılaştırıldı. Bulgular, mevcut senaryoda yüksek elektrik tüketimi nedeniyle artmış Deniz Akvatik Ekotoksikite Potansiyeli olduğunu, alternatif senaryonun ise gaz motorlarından kaynaklanan fazla CO₂ emisyonları nedeniyle artmış Küresel Isınma Potansiyeli gösterdiğini ortaya koydu. Bu zorluklara rağmen, piroliz etiket atıklarından enerji geri kazanımı için sürdürülebilir bir çözüm sunarak, atık yönetimi politikalarına ve döngüsel ekonomiye geçişte katkıda bulunmaktadır. Bu bilgiler, döngüsel ekonomi doğrultusunda sürdürülebilirliği teşvik etme ve fosil yakıtlara olan bağımlılığı azaltma potansiyelini vurgulamaktadır.

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LIST OF SYMBOLS/ABBREVIATIONS

Symbol	Explanation
CH ₄	Methane
CO	Carbon monoxide
CO ₂	Carbon dioxide
Fe	Iron
H ₂	Hydrogen
N ₂	Nitrogen
NO _x	Nitrogen oxides
NO ₂	Nitrogen dioxide
N ₂ O	Nitrous oxide
O ₃	Ozone
SO ₂	Sulphur dioxide
Abbreviation	Explanation
ADP	Abiotic Depletion
BAU	Business As Usual
BC	Before Christ
CML	Centre of Environmental Science of Leiden University
COD	Chemical Oxygen Demand
EC	Electrocoagulation
EF	Environmental Footprints
EPS	Expanded Polystyrene
EU	Europe Union
GHGs	Greenhouse gases
Gt	Gross ton
GWP	Global Warming Potential
HHV	High Heating Value
HIPS	High Impact Polystyrene
HTP	Human Toxicity Potential
ILCD	International Reference Life Cycle Data System
IPCC	Intergovernmental Panel on Climate Change
ITU	Istanbul Technical University

ISO	International Organization for Standardization
kcal	kilocalorie
kg	kilogram
km	kilometer
kWh	kilowatt hour
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LDPE	Low Density Polyethylene
lt	liter
LNG	Liquid Natural Gas
LULUCF	Land Use, Land Use Change, and Forestry
MAETP	Marine Aquatic Ecotoxicity Potential
MEA	Monoethanolamine
MJ	MegaJoule
MSW	Municipal Solid Waste
MW	Megawatt
n.d.	not detected
NF	Normalization Factor
NFs	Normalization Factors
PDM	Pressure Drive Membrane
PE	Polyethylene
PET	Polyethylene Terephthalate
PM	Particulate Matter
PP	Polypropylene
PS	Polystyrene
PSA	Pressurized Swing Adsorption
PUR	Polyurethane
PVC	Polyvinyl Chloride
R&D	Research and Development
SENTEK	Synthetic Fuels and Chemicals Technology Center
SDGs	Sustainable Development Goals
t	tonne

1. INTRODUCTION

In a world where urban living is rapidly increasing, the role of high-income countries in global waste production is not just significant but crucial. The 2015 global resource extraction increased 13-fold from 7 gross tons (Gt) to 89 Gt compared to 1900, indicating significant economic growth but also severe resource supply and waste management problems (Aguilar-Hernandez et al., 2021). Global solid waste generation has grown from less than 0.3 tonne (t) in 1900 to over 3.5 t in 2010, with projections indicating a double by 2025 and a triple by 2100. Global waste management, which includes all processes from waste generation through human activities to waste disposal, is a critical concept. Municipal solid waste (MSW), including commercial and household waste, is an important component of global waste management. Food and green account for 44%, paper and cardboard for 17%, plastic for 12%, and glass for 5% of the global waste composition, while the remaining includes metal, rubber, leather, and wood (World Bank, 2009). Worldwide, waste produced per day per person ranges from 0.11 to 4.54 kilograms and averages 0.74 kilograms. Although high-income countries are responsible for only 16 percent of the world's population, these countries are responsible for nearly 34 percent of the world's waste, which is 683 million metric tons (Kaza et al., 2018).

Paper waste has increased in recent years, with a significant amount disposed of in landfills. Over the last 40 years, paper consumption has increased by 40% globally, leading to a significant impact on deforestation, with 35% of felled trees used to produce paper. The European paper industry generates eleven million tons of waste annually, 70% of which comes from recycled paper production. Like paper, global plastic production has risen over the years because of the high amount of plastic produced in many industry sectors. In 2018, global production of plastic (excluding fibers) exceeded 350 million metric tons (Ozola et al., 2019). The increasing demand for plastic consumption and inefficient source separation still favor landfill disposal. Integrated waste management strategies prioritize prevention by codesigning, rethinking, and reusing, followed by mechanical and chemical recycling activities. Incineration and landfills are the final applicable technologies.

The European Union (EU) identifies primary principles for waste management. Waste management strategies aim to reduce or prevent waste generation and diminish its detrimental nature by creating clean technologies. When it is impossible to achieve or economically and environmentally feasible to implement these techniques simultaneously, companies should recover, reuse, recycle, or utilize waste materials as an energy source, as long as these actions improve or do not significantly

reduce the quality of the final product. Companies should safely dispose of waste in landfill areas as a final alternative.

Recovery operations treated over half (53.2%) of the waste in the EU in 2016, including recycling (37.8%), backfilling (9.9%), and energy recovery (5.6%). The remaining 46.8% either found their way into landfills (38.8%), underwent incineration without energy recovery (1.0%), or found alternative disposal (7.0%) (European Commission, n.d.).

The thermal conversion of waste through pyrolysis presents a promising and multi-faceted approach for mitigating its long-term environmental impact. There is a lot of potential in this thermochemical decomposition process, which breaks down complex polymeric chains into smaller hydrocarbon parts by using high temperatures and no oxygen. Pyrolysis not only yields liquid fuel oils (a potential renewable energy source), but also generates solid char and gaseous byproducts, adding further economic value to the waste stream. The recovery of fuel oils from waste plastics offers a compelling avenue for decreasing reliance on fossil fuels and promoting a more sustainable energy landscape. The sequence of waste management activities coherent with the idea of a circular economy includes the utilization of degradation products obtained from the pyrolysis process as an important part of the whole procedure.

The trajectory of waste generation poses significant challenges for waste management systems and exacerbates environmental degradation. Embracing a paradigm shift toward a "circular economy" is not just an option but an imperative necessity. This framework advocates for transitioning from a linear "make, use, discard" model to a closed-loop "make, reuse, recycle" system. By emphasizing the reduction of waste, the durability of products, and the regeneration of materials, a circular economy promotes both environmental sustainability and economic stability. The primary objective of the circular economy is to diminish the consumption footprint and enhance the recycling and reuse of materials within a closed-loop system (European Commission, 2020).

The European Environment Agency sees potential in chemically recovering valuable materials from plastic waste, according to a 2019 study by Wilts & Bakas (Wilts & Bakas, 2019). This method is gaining traction with researchers eager to create a circular economy for plastics. This situation means using recycled materials instead of virgin plastics, reducing reliance on fossil fuels and greenhouse gas emissions. Europe is at the forefront of this movement, adopting a strategy for a "smart, innovative, and sustainable plastics industry." This strategy places a high priority on designing and producing plastics that are easily reusable, repairable, and recyclable. By 2030, the EU

aims for all plastic packaging to be either recyclable or reusable cost-effectively. Additionally, changes in design and production are expected to boost recycling rates for various types of plastics. By 2030, it will achieve very high levels of separate collection for plastic waste (European Commission, 2018).

Chemical and energy recovery via pyrolysis of composite waste, which contains paper and plastics, environmental aspects of feedstock and processes, and the contribution of this method to the circular economy will be discussed.

The evolving landscape of waste management presents significant challenges. The growing heterogeneity of waste streams, coupled with societal expectations for cost-effective, environmentally responsible, and resource-preserving solutions, necessitates a paradigm shift towards circular economy principles. In this context, Life Cycle Assessment (LCA) emerges as a crucial and empowering tool for informing data-driven decision-making. By looking at all the environmental problems that come with different ways of dealing with trash, LCA gives everyone the power to find and use long-lasting solutions that meet society's needs and help create a circular economy (Christensen et al., 2020).

This study focuses on the evaluation of composite label waste consisting of a mixture of paper and plastic through pyrolysis, based on data obtained from ITU Synthetic Fuels And Chemicals Technology Center (ITU SENTEK), and examines the yields of the products obtained from this process as well as its environmental impacts in a assumed facility located in the Çerkezköy, Tekirdağ, Turkey. In a study conducted on two different scenarios, carbon-rich biochar, pyrolytic oil, and liquefied CO₂ were obtained in both cases; however, the product range and energy production methods varied between the scenarios. In the current scenario, the production of syngas and green liquefied natural gas (LNG) is carried out, while the alternative scenario aims for the production of green electricity and heat. The environmental sustainability of establishing a facility that contributes to green energy production and the circular economy in Turkey has been examined by evaluating all environmental impacts of the process using the gate-to-gate life cycle assessment method. In addition, this study will show essential clues for managing waste.

2. LITERATURE REVIEW

2.1. Waste Hierarchy

More waste piles up as populations grow, consumption habits shift, and economies develop. On a global scale, this has been evident: from 1.3 billion tons in 2010, waste generation ballooned to 2.0 billion tons in 2016, and projections estimate it will hit 2.59 billion tons by 2030 (Kaza et al., 2018). While wealthier countries produce the most waste, even poorer regions are witnessing significant increases, and this trend is expected to continue.

Waste disposal has been a pressing issue for centuries, with easy and affordable methods including dumping, burning, landfilling, stockpiling, and dumping into water bodies. The history of uncontrolled open dumping dates back to 10,000 BC, with ocean dumping, stockpiling, and landfilling practices emerging around 500 BC (Lamb et al., 2014). In response to the adverse effects of these practices, the European sanitary revolution, a slow 150-year progression, paved the way for the adoption of sustainable development approaches (Zaman & Lehmann 2011). These approaches prioritize waste reduction, reuse, recycling, and recovery over unregulated disposal.

The waste hierarchy serves as a strategic framework that promotes a circular economy. It guarantees the efficient use of materials to reduce waste. Furthermore, the waste hierarchy outlines the end-of-life journey of a product. Recovery, recycling, and reuse can reintroduce materials into the cycle, thereby promoting the efficient use of resources.

The waste hierarchy encompasses an initial evaluation of the necessity of purchases, advocating for the rejection of superfluous items. Strategies aiming at minimizing waste generation across industrial, household, and governmental sectors follow. Subsequently, it emphasizes resource recovery, which includes recycling, reuse, reprocessing, and energy recovery, in alignment with the practical application of recovered resources. Finally, disposal is addressed by the hierarchy, which implements the most environmentally responsible methods (Awino & Apitz, 2023).

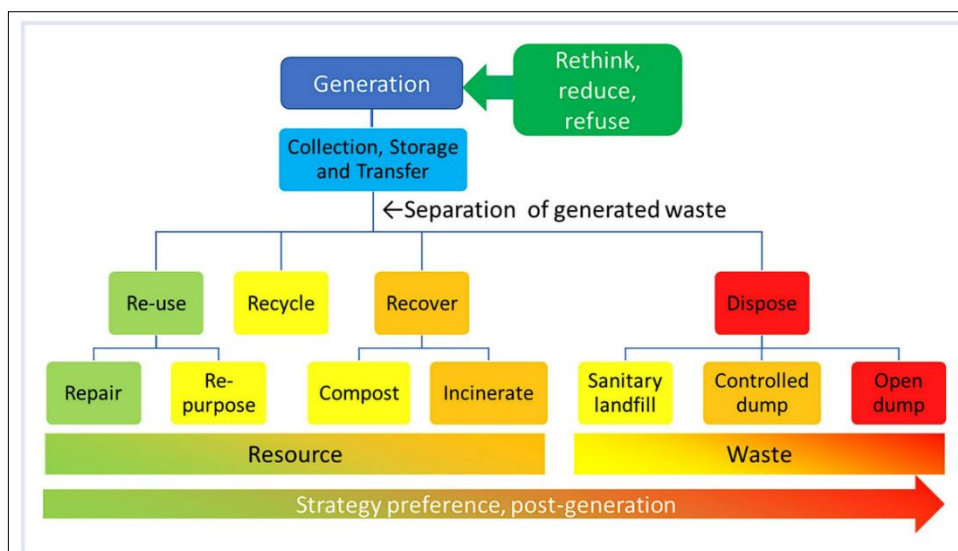


Figure 2.1. Waste hierarchy framework (Awino & Apitz, 2023).

2.1.1. Mechanical and Chemical Recycling

For mechanical recycling, reasonable quality improvement by utilizing additives is feasible but inversely comparable to the technical expense. Moreover, the possibility of implementing multiple recycling processes faces limitations. It is impossible to derive an exact common explanation regarding the impact of multiple recyclings on material-specific specialties of the recycles. It is also not possible for everyone to agree on how to use multiple recycling in the Circular Economy Model without replacing the recycled materials with additives. Because of these disadvantages, the investigators have turned their attention to chemical recycling to meet the high energy demand (Sharuddin S. et al., 2016). While heavily promoted, mechanical recycling requires careful sorting and high material purity to function effectively. Plastics can undergo a few cycles of recycling before their features diminish. Currently, the EU recycles just less than 30% of its plastic waste, with the remainder either incinerated or disposed of in landfill areas. Furthermore, mechanical recycling processes face some barriers, such as degradation of mechanical properties, cost, and incoherent quality products.

On the other hand, chemical recycling includes technologies that transform plastic waste into valuable feedstocks for the chemical industry. These feedstocks facilitate the creation of virgin-like plastics that maintain their properties and are suitable for any application. Several chemical recycling applications are under development, including pyrolysis, hydrocracking, depolymerization, and gasification. Compared to energy recovery options, chemical recycling via pyrolysis has a 50% lower climate change impact, lower greenhouse gas emissions, and lower life cycle energy use. Research in

waste pyrolysis indicates a more sustainable technology than other thermal degradation processes for the end of materials (Jeswani et al., 2021).

2.2. Circular Economy

The Ellen MacArthur Foundation (2015) defines the circular economy as designing products with repair and renewal. This economy ensures maximum usefulness and value throughout a product's life cycle. The foundation emphasizes differentiating how we approach materials based on their origin: technical cycles for non-renewable resources and biological cycles for renewable ones.

The 20th century scientific literature saw the explicit introduction of the circular economy concept. However, discussions on ideas like industrial ecology, cleaner technology, and sustainable development were already underway. The implementation and development of circular economy principles did not start in the 21st century, with Asia leading the way. Many EU member states are also adopting these principles, encouraged by the European Commission (Szczerbak, 2022).

The circular economy aims to eliminate waste and extend product life cycles altogether. Through reuse, repair, and recycling, the lifespan of resources is extended by preventing them from ending up in landfills. Keeping materials in use reduces waste and encourages efficient resource use, renewable resources, and reasonable consumption. Even before products are discarded, efforts are made to design them with future reuse or recycling in mind. Ultimately, the circular economy changes how we think about customers, markets, and resources, promoting a more sustainable approach (Szczerbak, 2022).

Efficient waste management is critical for ensuring uninterrupted production continuity. This necessitates a comprehensive understanding of the qualitative and quantitative composition of the waste generated. Such knowledge facilitates the optimization of segregation processes, highlighting the crucial role of waste management in business operations. Furthermore, carefully selecting the number and dimensions of collection receptacles is critical for streamlining waste disposal while maintaining the integrity of segregated fractions. Finally, post-production waste management requires a meticulous evaluation of reutilizable and recyclable options based on the inherent physical and chemical properties of the materials. These valorizable resources, including paper, plastics, glass, and ferrous and non-ferrous metals, have the inherent ability to repeatedly enter the production cycle. Paper, for example, can undergo reprocessing up to six or seven times, whereas plastics can undergo reprocessing up to ten times.

Efficient waste management in enterprises demonstrably reduces waste, optimizes business functions, saves employee time, and enhances safety while achieving environmental goals. Implementing the waste hierarchy, which prioritizes minimization, reuse, recycling, and material recovery, offers opportunities for material circularity and demonstrably improves financial outcomes. By highlighting the financial benefits, this information can motivate organizations to readily embrace this approach and prioritize product recovery strategies so that they can create a sustainable future (Szczerbak, 2022).

2.3. Pyrolysis

Pyrolysis is the thermochemical decomposition of organic material in the absence of oxygen and at high temperatures (400–1000 °C). In other words, in Figure 2.2., pyrolysis is defined as the direct thermal decomposition of organic materials to produce gas, liquid, and solid products. This technique is gaining attention due to its flexibility in producing a composition of solid, liquid, and gaseous products in different ratios, which is made possible by the diversity of operating conditions such as temperature and heating rate. Pyrolysis temperature has a noticeable effect on products' volatile yield and yield distribution. Besides these, pyrolysis produces fewer emissions from air pollutants than other thermal decompositions. In addition to these benefits, pyrolysis generates lower emissions of air pollutants compared to other thermal decomposition methods. This technology also enables the extraction of valuable chemicals and the conversion of low-energy-density materials into biofuels with higher energy density (Czajczynska et al., 2017).

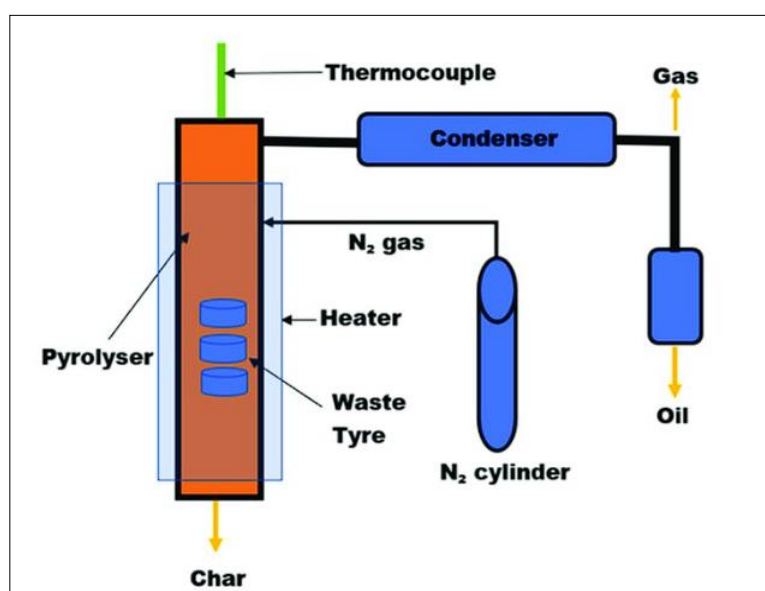


Figure 2.2. Diagram of a pyrolysis reactor (Jahirul et al., 2021).

The pyrolysis temperature can alter the composition and character of the products. Other than temperature, many parameters, such as heating rate, particle size, rotation speed, and residence time, influence the efficiency of the products throughout the process. For example, oil is the prevalent product during rapid heating rates, whereas slow heating rates result in a prevalent solid product. Also, the gas particles tend to rise with increased pyrolysis temperatures (Efika et al., 2015). Figure 2.3 summarizes the impact of factors such as temperature, residence time, feedstock composition, heating rate, catalyst usage, and condensation on the formation of liquid fuel, gases, and char (solid residue) during the thermal pyrolysis process. While higher temperatures favor the production of gaseous and liquid products, lower temperatures result in increased char yield. Although liquid fuel can be obtained in high yield, it often contains impurities and exhibits a low octane number. Gases are typically rich in CO and CO₂, whereas char is characterized by a high carbon content. The process requires careful optimization to ensure energy efficiency and product quality.

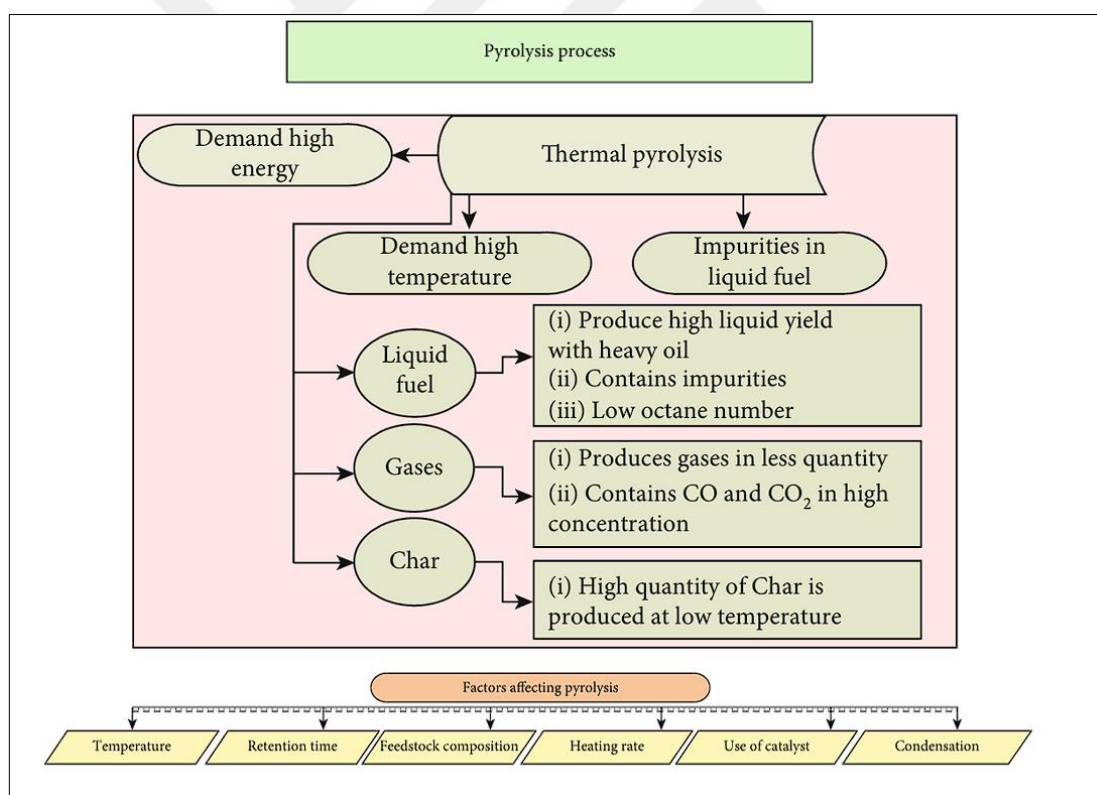


Figure 2.3. The sample of pyrolysis process of waste (Kabeyi & Olanrewaju, 2023).

Pyrolysis is a very beneficial process that converts waste into valuable fuel and raw materials, which may be utilized in the production of new products like plastic and paper. It acts as an environmentally valid option for incineration and inefficient landfilling (Nallusamy, 2022). The fundamental principles of pyrolysis, along with recent advancements, diverse activity states, and

associated residuals, are crucial for the integration of pyrolysis into plastic recycling within the waste management sector (Czajczyńska et al., 2017).

This study investigated the challenges and opportunities associated with plastic waste management. It assessed pyrolysis's potential as a plastic recycling technology with a lower environmental impact than other alternatives. Perugini's study demonstrates that integrating low-temperature pyrolysis with mechanical recycling of plastic waste reduces the carbon footprint of plastic landfilling by 67% and reduces it by 76% when compared to plastic incineration (Qureshi et al., 2021). During the pyrolysis process, the input of exterior energy supplies the essential heat for thermal wastes' decomposition. Pyrolysis of wastes, as opposed to incineration, prevents significant dioxin formation and reduces the generation of nitrogen oxide (NO_x). This is due to the lower temperatures and inert conditions, which reduce the oxygen content in the tank's atmosphere to 8% or less by volume through the addition of inert gas (Zhang, 2020).

Dai et al. (2022) claim that pyrolysis can convert plastics into naphtha. This conversion allows waste plastics to be recovered as feedstock for new plastic production, reducing the need for fossil fuels and facilitating waste plastic recycling. The Ruan Group in California has developed a facility capable of converting 1.5 tons of plastic waste per day into naphtha, while a Danish company has developed a plastic-to-naphtha conversion technology that can process 20,000 tons of plastic solid waste (PSW) annually. Research has shown that the quality of plastics produced using plastic-to-naphtha conversion technology is the same as that produced from fossil fuels.

Feedstock composition plays a crucial role in determining product formation during pyrolysis processes. Ojha and Vinu (2015) demonstrated this role by investigating the pyrolysis of feedstock containing varying ratios of polypropylene (PP) and cellulose. The results show that co-pyrolysis with PP lowers the amount of oxygen in the end products by a large amount compared to pyrolysis of pure cellulose. This deoxygenation effect is most pronounced when the cellulose content is around 50%. Furthermore, the study identifies a significant enhancement in alcohol yield with increasing PP content in the feedstock. With an assessment of the quality of the generated products, researchers have discovered that during pyrolysis, cellulose and PP react with each other to form a higher-quality liquid product. This liquid product was particularly rich in C8–C20 alcohols and C6–C15 hydrocarbons. These compounds are among the main components of gasoline. High-temperature co-pyrolysis (600 °C) also resulted in a more efficient product.

In pyrolysis, temperature is a critical parameter that significantly influences the properties and quantities of the generated products. Ozcakir and Karaduman (2020) conducted experiments at various temperatures (470, 520, 570, and 620 °C) to examine the impact of temperature on the product distribution of co-pyrolyzed polystyrene (PS) and low-density polypropylene (LDPE). The experiments involved mixing PS and LDPE in equal proportions (50:50) and pyrolyzing them at the specified temperatures. At 570 °C, the maximum liquid product yield of 83.5% is obtained, while the solid product yield decreased from 3.9% to 0.3% as the temperature increased. This alteration indicates that pyrolysis reactions proceed more vigorously at higher temperatures, leading to the breakdown of solid products. For all temperatures, the gas product yield remained consistent at approximately 20%.

2.3.1. Pyrolysis of Plastic Waste

When examining plastic demand and composition in Europe, polypropylene (PP), polyethylene (PE), polyvinyl chloride (PVC), polyurethane (PUR), polyethylene terephthalate (PET), and PS dominate overall demand, while PE, PP, PS, PET, and PVC represent the majority of plastic encountered in municipal solid waste (López et al., 2011). Unlike organic materials, plastics exhibit minimal biodegradation, rendering landfill disposal undesirable. Incineration also garners controversy due to potential emissions of toxic and greenhouse gases, particularly dioxins and furans, which require exceptionally high temperatures to mitigate. Additionally, traditional incineration eliminates valuable organic matter. Seeking alternative solutions, Sharuddin et al. (2016) advocate for pyrolysis as a promising technology for converting plastic waste into valuable resources. They highlight the flexibility of pyrolysis, allowing for tailoring operating parameters to yield desired products like liquid oil, gas, and char.

The type of plastic used in pyrolysis significantly impacts the amount and type of products formed. Calero et al. (2023) found that temperature matters in controlling the oil-to-gas ratio, with the best oil yield achieved at 500 °C after one hour of pyrolysis. Increasing the temperature above 525 °C slightly reduces oil production for materials like PE, PP, expanded polystyrene (EPS), and high-impact polystyrene (HIPS). Notably, PET and PVC generate very little oil and char because they contain elements other than carbon and hydrogen. During pyrolysis, the dominant gas released differed based on the polymer used. EPS, PP, and PVC peaked at around 70% methane content within 40–80 minutes, while PE and HIPS maxed out at 50% methane. Methane dropped sharply in EPS and PP pyrolysis after 80–100 minutes. Besides methane, ethane was commonly detected. Other gases like hydrogen, propane, and butane appeared in smaller amounts. PET, however, stood out by

primarily releasing carbon dioxide (CO₂), likely due to its oxygenated monomer. This CO₂ gradually declined over time, with ethane and methane emerging as secondary products (Calero et al., 2023).

Donaj and his colleagues (2012) experimented with the co-pyrolysis of a mixture of polyethylene and polypropylene at 650°C and 728°C. Although a small amount remained as solid residue (less than 15%), the majority turned into gases (37% and 42%, respectively) or liquids (44% and 48%, respectively). Higher temperatures favored the production of lighter and more desirable liquid fractions over heavier, less valuable ones like carbon black, wax, and heavy oil.

2.3.2. Pyrolysis of Paper Waste

The paper serves diverse purposes across industries and cultures, from coffee filters to textbooks. It makes up a significant component of combustible waste, accounting for roughly one-third of typical municipal trash. However, its low nitrogen and sulfur content makes it an ideal fuel source, potentially offering a sustainable waste-to-energy solution. Researchers have studied the thermal degradation behavior of a variety of paper wastes.

Li et al. (2005) investigated waste paper pyrolysis at various heating rates and temperatures to determine the yield of pyrolysis products and bio-oil composition. They discovered that a heating rate of 30 °C/min at 420 °C yielded the maximum oil yield (49.13%). The yield increased with increasing temperatures. At 450 °C, the highest gas yield (18.23%) is obtained and the lowest char yield (33.43%). At higher temperatures, the presence of char and primary vapors in secondary degradation reactions enriched the gaseous product. The results showed that the oil consists of many different chemical classes, including four main compounds: anhydrosugars, carboxyl compounds, carbonyl compounds, and aromatic compounds.

Zhou et al. (2013) subjected printing paper and cardboard to pyrolysis, a thermal decomposition process, at temperatures of 400, 500, and 600 °C. Their findings revealed a rising syngas yield with increasing temperatures, as well as a decline in char and tar production. The primary components of the generated gas were methane (CH₄), CO, CO₂, and hydrogen (H₂), along with lighter C₂ to C₄ hydrocarbons. Notably, the pyrolysis temperature directly influences the specific concentrations of these gases. Aromatic compounds such as naphthalene, phenols, benzofuran, benzenes, and cyclopentenenes predominantly composed the tar fraction, with minor aliphatic components present.

2.3.3. Pyrolysis of Composite Wastes

Conventional recycling struggles with mixed plastics contaminated by paper, textiles, and food. Complex composites, such as those coated with plastic films and paper cups, further challenge sorting and pollute other streams, like paper. Pyrolysis, a thermal decomposition process, offers promise for unsorted mixed plastics. This pyrolysis liquid product can be converted into valuable fuels and chemicals, even from mixed municipal waste plastic. Pyrolysis presents a potential solution for efficient processing and valorizing this problematic waste stream (Chen et al., 2019).

Haydary and colleagues (2013) investigated using pyrolysis to break down waste containers consisting of 70% Kraft paper, 25% polyethylene, and around 5% aluminum foil in a way that produces the most gas possible while minimizing the formation of tar. Higher temperatures led to more carbon monoxide (CO) and hydrogen in the gas, while reducing the amount of hydrocarbons and liquid products. At 850 °C, the peak gas yield reached 86%. The condensed liquids included both oil and water. As the temperature increased, the ash content in the remaining char residue rose from 21% to 26%. Based on their findings, the researchers concluded that pyrolysis offers a promising method for handling waste packaging. However, further research is necessary to optimize the process and make it economically feasible.

Ojha and Vinu (2015) showed that combining biomass (cellulose) and polymers during fast pyrolysis can create high-quality biofuels. Their experiments revealed that mixing these two materials primarily produces long-chain alcohols (C8–C20). Mixtures heavy in PP produced a significant amount (around 34%) of C6-C15 hydrocarbons at high temperatures (500°C and 600°C). These higher temperatures also produced monoaromatic and polyaromatic hydrocarbons, while reducing char formation. The bio-oils produced had heating values between 36 and 41 MJ/kg, and there was a strong link between the oil's heating value and the total amount of alcohol, aliphatic, and aromatic hydrocarbons. According to the researchers, transferring hydroxyl groups from cellulose to polymers is the critical reaction behind alcohol formation, along with other reactions involving cellulose and free radicals from PP breakdown.

2.4. Life Cycle Assessment

2.4.1. Life Cycle Assessment Methodology

Understanding the main environmental impact of any recycling process requires a thorough and unbiased assessment of all its environmental consequences. A recognized and standardized tool, life cycle assessment, allows for the tracking of environmental costs and benefits throughout the entire life cycle of a product or service, from raw material extraction to final disposal. Essentially, it is the best way to move beyond general claims about environmental benefits and accurately determine how sustainable a recycling system is. LCA takes a big-picture approach to evaluating the environmental impact of products and processes. Unlike other methods focusing on single stages or issues, LCA considers the entire lifespan, from raw material extraction to disposal. This comprehensive perspective enables us to identify and address potential problems before they occur, as well as find ways to minimize environmental harm across different stages, regions, and impact categories. In recent years, LCA has become a valuable tool for promoting sustainable practices and reducing the environmental footprint of products and processes (ISO 14040, 2016).

LCA delves into the environmental footprint of a product or service, cradle-to-grave. This in-depth analysis unfolds in four stages: setting the goals and scope, inventorying life cycle inputs and outputs, assessing environmental impacts, and interpreting the findings (ISO 14040, 2006). First, the LCA defines its purpose, target audience, and boundaries. This stage explains who needs the information and where the product or process operations begin and end. Also, this establishes the "functional unit," a quantifiable measure of the product's function, allowing for fair comparisons between different products. The life cycle impact assessment (LCIA) then converts the life cycle inventory (LCI) data into environmental impacts such as climate change, resource depletion, and human health effects. This stage employs established methodologies to quantify and categorize these impacts, revealing the product's environmental burden. The selection of impact categories in a life cycle assessment is contingent upon the specific objectives of the analysis, and the limitations imposed by the availability of data and inherent in existing impact assessment methodologies. The explanation of the four impact categories examined in this study are presented below. Furthermore, the impact assessment process includes a normalization step. Normalization provides three fundamental technical benefits. Firstly, it enables comparative analysis between various environmental impact categories, which is essential for verifying the reasonableness of the results. By scaling all impact categories to a common baseline, the relative significance of each category can be assessed, and potential inconsistencies can be identified. Secondly, it enhances the communication

of LCA results. The normalization step transforms impacts into a consistent and unified scale, facilitating the understanding of results by stakeholders, including policymakers and the general public (Pizzol et al., 2016). Lastly, normalization plays a crucial role in facilitating the subsequent weighting step, which allows for the prioritization of different impact categories according to their importance. This step eliminates the unit dependency inherent in LCA data, enabling a more objective comparison of the environmental performance of various impact categories (Jolliet et al., 2003). For instance, without normalization, impacts such as GWP measured in CO₂ equivalents cannot be directly compared to impacts like acidification measured in SO₂ equivalents. Finally, interpretation brings it all together. The LCA draws conclusions and offers recommendations by analyzing the data in light of the initial goals and scope. This stage is crucial for informing decisions about product improvement, resource optimization, and achieving sustainability (ISO 14040, 2006). For example, researchers have applied LCA to diverse areas like residential buildings and wastewater treatment plants (Mishra et al., 2021). These studies demonstrate LCA's versatility as a powerful tool for understanding and minimizing environmental impacts across various products and services.

2.4.1.1. Abiotic Depletion (ADP). Abiotic depletion potential (ADP) is a characterization factor employed in life cycle assessment studies to quantify the depletion of natural resources, such as minerals and fossil fuels, resulting from human activities. Depletion occurs when the extraction rate exceeds the natural replenishment rate, resulting in a finite supply of these resources. The depletion of abiotic resources poses many environmental and socioeconomic challenges that demand urgent attention. The current primary method relies on two distinct issues: the depletion of elements and a reduction in total natural reserves (in kg), the depletion of fossil fuels, and the depletion of total natural energy reserves (MJ) (Guinée et al., 2001). However, this study does not delve into the examination of natural reserve depletion.

2.4.1.2. Global Warming Potential (GWP). The LCA uses Global Warming Potential as an impact category to evaluate the potential contribution of a product, process, or service to global warming. The kilogram (kg) of carbon dioxide equivalent (kg CO₂-eq) is a standard unit that is used by GWP to measure emissions of different greenhouse gases (Seile et al., 2022).

2.4.1.3. Human Toxicity Potential (HTP). Human Toxicity Potential (HTP) is a quantitative metric designed to assess the potential adverse effects exerted by a unit of a chemical released into the environment. This metric integrates both the inherent toxicological profile of the compound and its estimated exposure level. HTP values for each toxic substance are expressed in 1,4-dichlorobenzene equivalents per kg of emission (Hertwich et al., 2001).

2.4.1.4. Marine Aquatic Ecotoxicity Potential (MAETP). Within the framework of Life Cycle Assessment, the Marine Aquatic Ecotoxicity Potential (MAETP) is a number that measures how much damage a product or process might do to marine ecosystems. This methodology explicitly targets the detrimental effects of substances discharged into saltwater ecosystems encompassing oceans, seas, and estuaries. MAETP values for each toxic substance are expressed in 1,4-dichlorobenzene equivalents per kg of emission (Ozturk & Dincer, 2020).

2.4.1.5. Acidification Potential (AP). Acidification Potential (AP) is an environmental impact indicator within LCA that quantifies the potential of acidic gases (such as sulfur dioxide and nitrogen oxides) to accumulate in the atmosphere and cause acid rain. This impact is closely associated with the use of fossil fuels, agricultural fertilizer application, and industrial emissions. AP serves as a critical tool for understanding and mitigating the negative effects of these activities on the environment. LCA studies employ AP calculations as an essential parameter for evaluating environmental sustainability and assessing impacts (Guinée, 2002).

Life Cycle Assessment is software that interprets a product's potential environmental impacts. It determines the environmental impact of a specific product by gathering data about its effect. The LCA examines the yield distribution of products by varying the process parameters. This assessment not only obtains the results but also makes process comparisons. For this reason, operating parameters and composites of raw materials are vital for pyrolysis (Christensen et al., 2020).

A diverse range of software, including GaBi, SimaPro, Umberto, and Integrated Waste Management, effectively facilitates LCA. GaBi excels in product-related LCAs thanks to its expansive and documented database. This database empowers LCA practitioners to understand a product's environmental footprint and impact throughout its life cycle (Sunday et al., 2022).

2.4.2. Life Cycle Assessment Application in Paper and Plastic Waste Management

Effective waste management is a cornerstone of sustainable development, with far-reaching benefits for public health, the environment, and the climate. As interest in sustainable resource and waste management grows, the role of Life Cycle Assessment (LCA) becomes increasingly significant. LCA serves as a valuable tool for making informed decisions when choosing waste management systems or prioritizing resource use, as it provides a comprehensive view of the environmental impacts of various options (Cherubini, 2009).

LCA considers the potential environmental effects and aids utilized in a waste management technique. The comprehensive goal of a waste management LCA is to establish a comprehensive overview of all the processes involved in pyrolysis. Decision-makers can utilize LCA methodologies as a source of data to select waste management or make crucial choices about resource usage priorities. An LCA can provide environmental views of various waste management schemes and make it feasible to analyze the possible environmental impacts of these alternatives. Despite its simplicity, implementing Life Cycle Assessment (LCA) on waste management systems reveals a crucial insight: every waste management activity contributes to the environment, either through direct emissions or the environmental effects of the materials and energy used to operate the system. The environmental rescue comes from the energy and recovered materials used as substitutes for other matters and energy that would have imposed a burden on the environment. Let's assume that there is a clear understanding of energy and material recovery. In this scenario, the Life Cycle Assessments (LCAs) of waste management schemes often demonstrate that the environmental benefits outweigh the costs, revealing that the recovery of energy and resources from waste nearly results in a positive environmental impact (Istrate et al., 2020).

The burgeoning production of plastics necessitates the development of robust waste management practices to curb environmental degradation. LCA is a potent tool for assessing the environmental implications of various plastic waste management strategies. LCA facilitates informed decision-making by offering a comprehensive analysis of the environmental burden throughout the entire lifecycle, encompassing raw material extraction, production processes, and end-of-life treatment or disposal. LCA empowers the identification of the most sustainable approaches tailored to specific waste streams and contexts by quantifying and comparing the environmental impact of various waste management options such as recycling, incineration, landfilling, and waste-to-energy conversion. LCA is a powerful tool for assessing the environmental impact of paper waste management, just like plastic waste management. It considers the entire lifecycle of paper, from raw material (tree) extraction to its production, consumption, disposal, and potential recycling. Effective waste management is crucial for environmental sustainability. Demetrious and Crossin (2019) employ an LCA methodology to evaluate the most suitable waste management strategies for paper and plastic waste streams. The LCA framework encompasses three waste management options: recycling, incineration, and landfilling. The findings suggest the implementation of separate waste management systems for paper and plastic waste. Adhering to the waste hierarchy (recycling, energy recovery, and disposal) is the most environmentally sound approach for paper waste. The study also highlights landfilling's negative environmental impacts, primarily due to emissions from paper waste

decomposition and leachate from plastic waste. These findings underscore the necessity of tailored waste management strategies for different recycling materials.

Costa et al. (2022) highlighted the need for LCA studies of chemical recycling through polyolefin pyrolysis to be more representative. They should consider factors like time, location, and technology variations. On the other hand, pyrolysis experiments should prioritize maximizing carbon conversion efficiency and using renewable energy sources. The last step is to compare the LCA results, paying special attention to the type of plastic used (recycled, fossil, or renewable), and ideally without any expansion (attributive LCA). This comparison provides a clearer picture of the actual environmental footprint of each approach. In addition, LCA modeling of waste management systems allows for broad quantification of chemical recovery from paper and plastic wastes, as well as possible environmental effects. This quantification can be based on specific periodicities, providing a basis for monitoring progress toward future goals such as CO₂-neutrality (Christensen et al., 2020).

3. MATERIALS AND METHODS

The LCA methodology, following the International Organization for Standardization (ISO) content for ISO 14040 and 14044 (ISO 14040, 2006; ISO 14044, 2006), was employed to assess the environmental impacts throughout the production lifecycle of liquid natural gas (LNG) and electricity derived from label waste. This label waste is made up of 85% cellulose and 15% plastic. It is broken down in a pyrolysis facility assumed to exist in Çerkezköy, Tekirdağ. This facility is thought to exist based on data from GaBi 8.0 software, data obtained from the ITU SENTEK, market research, and relevant academic literature. With its potential to generate green energy from label waste, the pyrolysis system presents a promising scenario where the generated syngas serves as the system's energy source.

Waste pretreatment, pyrolysis process, cooling systems, wastewater treatment, amine scrubber and amine regeneration, CO₂ liquefaction, pressure swing adsorption, syngas deposition, and LNG liquification systems are all part of the study. The functional unit is the 1 kg/hour label waste entering the pyrolysis facility for treatment. Environmental impacts were assessed using GaBi 8.0 software and CML 2001, applying the impact assessment methodology across various categories (abiotic depletion, global warming potential, human toxicity potential, marine aquatic ecotoxicity potential).

3.1. Goal and Scope Definition

The effective management of waste generated has become one of the most urgent environmental issues of our time. Particularly, composite label wastes, which combine plastic and paper components, significantly burden traditional waste management systems. This study examines the high-temperature pyrolysis method using the life cycle assessment (LCA) method to convert these wastes into energy, aiming to reduce waste volume and produce clean energy

Traditional incineration methods as seen in Figure 3.1., although preferred for the rapid disposal of waste, increase their negative impact on climate change by leading to high levels of greenhouse gas emissions. This situation has become even more critical in today's world, where the transition to sustainable energy sources has become imperative. The pyrolysis process, on the other hand, stands out as a thermochemical conversion process that transforms waste into energy-dense gas products by exposing it to high temperatures in an oxygen-free environment.



Figure 3.1. Incineration method.

This study will comprehensively examine various aspects of pyrolysis, including its potential to reduce greenhouse gas emissions, energy efficiency, and the evaluation of by-products, to provide a more environmentally sustainable alternative for label waste management. The traditional disposal method of incineration is accepted as the baseline method. In the results section, the current and alternative scenarios will be evaluated and compared, and then the baseline method will be presented by comparing it with these two scenarios. By including an analysis of the incineration method, this study aims to provide a clearer assessment of the pyrolysis method from an environmental perspective. Comparing pyrolysis with incineration, a widely adopted method, allows for a concrete evaluation of its advantages and disadvantages. In this way, the study not only aligns with the existing literature but also seeks to present decision-makers with insights into the potential environmental benefits of alternative methods.

This work also aims to optimize the yield of gaseous products derived from label waste via high-temperature pyrolysis. The primary impetus for this methodology is the possibility of the gas mixture produced during pyrolysis to serve as a sustainable energy alternative to natural gas, owing to its elevated calorific value and the inclusion of useful constituents such as CO and H₂. About 20% of the generated syngas will be consumed internally to satisfy energy requirements, whereas the remaining 80% will serve as an energy source across diverse businesses. This approach targets both the reintegration of trash into the economy and the diminishment of reliance on fossil fuels. The high-yield gas product generated will improve the energy efficiency of the pyrolysis process, rendering it more sustainable. In addition, the production of green LNG represents a significant step towards transitioning to more sustainable and environmentally friendly energy sources, replacing fossil fuels. Compared to electricity generation, the advantage of green LNG lies in its portability and storability; it enables energy to be transported and stored on an international scale, thereby ensuring energy security while enhancing the integration of renewable energy sources. Moreover, green LNG can replace conventional natural gas, reducing dependency on fossil fuels, lowering greenhouse gas emissions, and playing a crucial role in combating climate change. In this context, the production and utilization of green LNG are vital components in building sustainable energy systems, offering a critical alternative in terms of energy storage and transportability.

GaBi8 software, one of the LCA programs, will analyze the data from the laboratory pyrolysis study. ITU SENTEK will provide the data inventory for this study on the pyrolysis process. This laboratory is a research and development (R&D) center that conducts R&D studies for the thermochemical conversion processes used to produce synthetic fuels, green methane, green electricity, pyrolytic oil, and carbon-rich biochar from composite wastes. The GaBi8 software will process the primary data obtained from the laboratory. It is essential to ensure data quality for the LCA study to yield dependable results. As a result, raw data from the studies' results will be turned into data that can be processed in the LCA software. The necessary studies will be carried out according to the LCA methodology to get expressive results. All the information in the study, except for the pyrolysis data, will come from the literature and market research.

3.1.1. Functional Unit

It is defined as "the quantified performance of a product system for use as a reference unit" and should be consistent with the study's goal and scope (ISO 14044, 2006). This study defines the functional unit as 1 kg/hour of label waste entering the pyrolysis facility for treatment.

3.1.2. System Boundaries

The system boundary, which must be consistent with the study's scope and objective, defines the unit processes to be contained in the study (ISO 14044, 2006). The LCA study consists of two different systems and a traditional method. The scenarios and the traditional method addressed in this study are briefly described below. The details of all these scenarios and the traditional method are discussed in subsequent sections. The current system is shown in Figure 3.2.

3.1.2.1. Current Scenario. The primary scenario is defined as the current scenario. In this scenario, label wastes are subjected to pyrolysis and other processes to produce carbon-rich biochar, pyrolytic oil, syngas, and green LNG. A portion of the syngas obtained is used as an energy source for the pyrolysis system, while the remainder is supplied to other facilities as an energy source. The green LNG produced is either fed into the natural gas grid or utilized as fuel in transportation.

3.1.2.2. Alternative Scenario. In the alternative scenario, label wastes undergo pyrolysis and other processes to produce carbon-rich biochar, pyrolytic oil, as well as electricity and heat energy. As in the current scenario, the energy requirement of the pyrolysis system is met by the syngas it produces.

3.1.2.3. Baseline Method – Incineration. The traditional incineration method involves the combustion of label wastes solely for energy production.



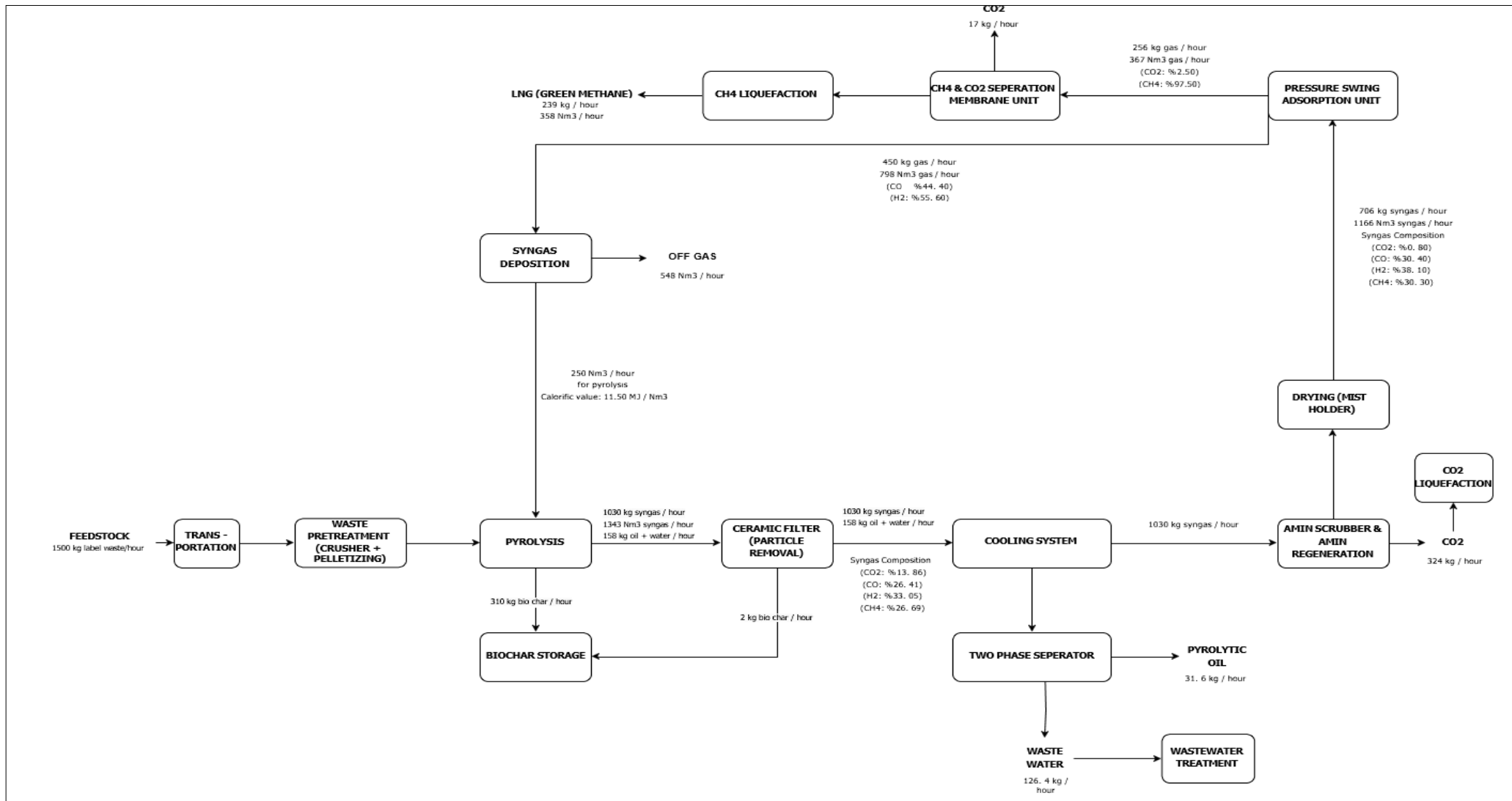


Figure 3.2. The schematic diagram of current scenario.

First, diesel fuel trucks bring label waste, consisting of 85% cellulose and 15% plastic, to the pyrolysis facility in Çerkezköy. The facility initially feeds the waste to the pyrolysis reactor through the pretreatment phase. The pretreatment phase consists of two processes. The feedstock first undergoes the appropriate size reduction crushing process, after which it undergoes the pelletizing process with a bulk density of 0.25 to 0.35 kg/cm³. With the pelletizing process, the bulk density of the waste increases to 0.70–0.80 kg/cm³. It increases the amount of energy produced by pyrolysis through the pelletizing process because the high bulk density of the pellet implies a higher energy density of the feedstock (Madadian et al., 2017). During crushing, a small amount of dust may form, but since this amount is negligible, it is assumed that no particulate matter (PM) forms at this stage.

The pyrolysis reactor plays a pivotal role in the waste treatment process, initially heating with natural gas. After approximately 3 to 4 hours, the temperature of the auger-type fast pyrolysis reactor reaches 850°C at 10 rpm. When the temperature reaches 850°C, the composite waste from the pretreatment enters the pyrolysis reactor. To obtain syngas and char, the feedstock entering the reactor undergoes thermal decomposition in an oxygen-free environment at high temperatures with a fast heating rate. The facility produces syngas to meet the reactor's energy needs after this point.

The waste-pyrolysis process is not only environmentally beneficial but also highly efficient. The pyrolysis process forms carbon-rich biochar at a rate of 312 kg/hour. The cement factory purchases the resulting biochar. The incorporation of biochar into cement-based materials presents a promising avenue for mitigating the significant carbon footprint associated with conventional construction practices. Biochar's porous structure facilitates cement hydration acceleration, a process that demonstrably enhances CO₂ uptake by the cement itself. This happens in a way that works with itself to store carbon twice: first, in the biochar itself; and second, through the improved CO₂ absorption of the modified cement composite (Song et al., 2023). On the other hand, the syngas from the pyrolysis process enters the thermal reformer unit for tar removal at 750 °C. The pyrolysis of composite wastes not only produces syngas but also produces tar. The thermal reformer is used to remove tar from the syngas before subjecting it to further processing. The gas released as a result of the pyrolysis process may contain particles that can harm human and environmental health. Ceramic filters trap these particles and clean the gas. After tar removal, the gas passes through the filter material, the particles adhere to the filter surface, and particle removal occurs at 400 °C (Gao et al., 2018). A high-efficiency ceramic filter effectively removes char from the syngas stream. Residual biochar carryover is estimated to be minimal, at approximately 1 wt.%. A dedicated fan system subsequently entrains this minimal biochar fraction with the main biochar product stream as it exits the pyrolysis unit.

The gas leaving the ceramic filter enters the heat exchanger for separation and purification. The chiller cools the water, which then meets the syngas in the heat exchanger. The exchanger's cooling separates the gases and liquids at this stage. Gases condense and become liquid, as shown in Figure 3.3.

The amine scrubber receives the separated gas, while the two-phase separator separates liquid phases with different densities and purifies them from contaminants. A two-phase separator sends 80% of the liquid to the wastewater treatment unit as wastewater, while it forms 20% pyrolytic oil.

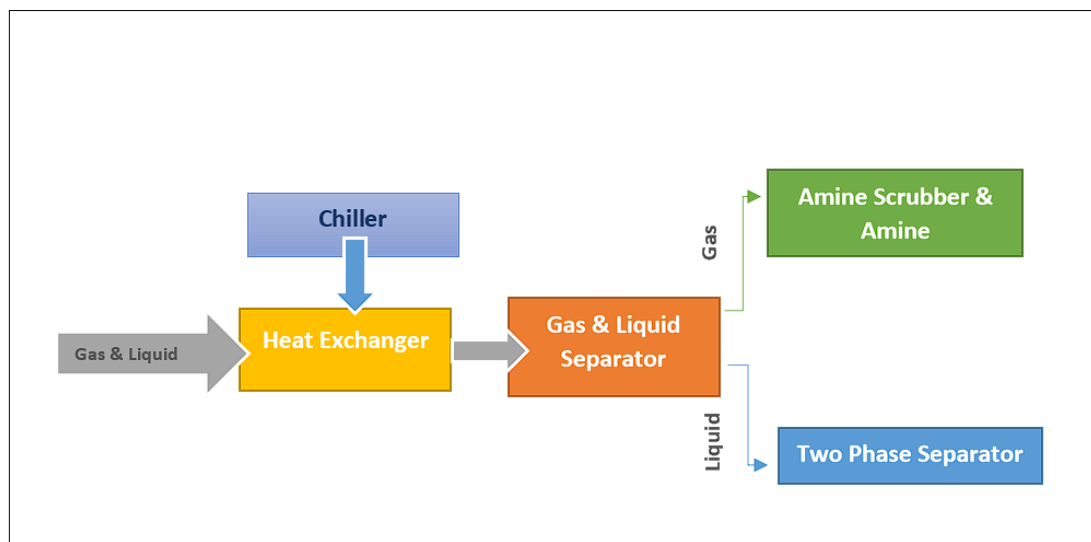


Figure 3.3. Cooling system.

Based on research findings, the electrocoagulation (EC) method was chosen for wastewater treatment in the scenario. Many recent studies have focused on electrocoagulation, mainly due to increasing environmental restrictions on effluent discharges. In the EC process, researchers have mostly used aluminum and iron as electrodes to treat wastewater from paper mills. They found that this method worked best for getting rid of pollutants when the pH level was between 6.7 and 7.7. They used the EC process with an aluminum electrode to treat wastewater from a paper mill. At a pH of seven and a running time of fifty minutes, it removed 98% of the chemical oxygen demand (COD) and 99% of the color (Yılmaz & Karagözoğlu, 2019).

The amine scrubber uses a process involving monoethanolamine (MEA) at a 15 wt% solution concentration in water at 25°C to remove harmful and undesirable gases from the gas entering it.

The two-stage amine scrubbing process for CO₂ capture is a highly efficient system. It uses absorption and regeneration columns, with either random or structured packing inside. This allows

for continuous refreshment of the amine solvent, thereby minimizing solvent loss. Figure 3.4. depicts a schematic representation of this robust scrubbing process (Khalid et al., 2022).

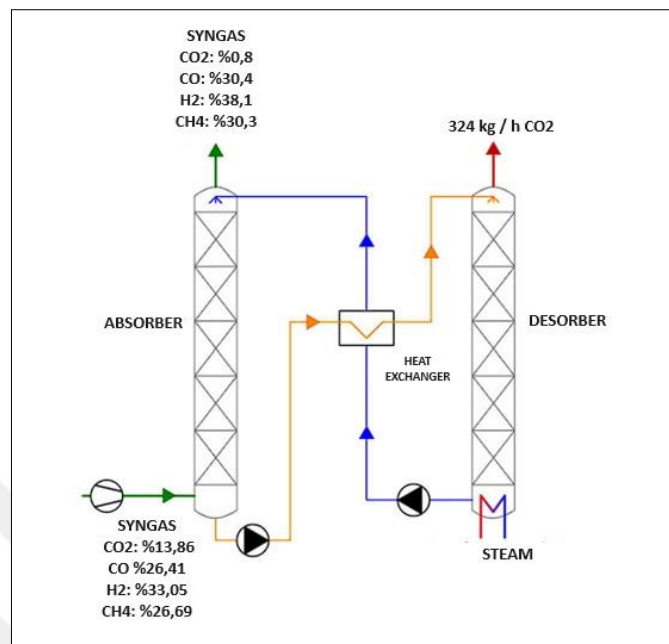


Figure 3.4. Amine scrubber and regeneration.

Flue gas undergoes a preliminary cooling stage prior to entering the CO₂ absorption column. This stage reduces the gas temperature to a range of 25 °C. Additionally, compression is employed to counteract pressure drops within the column. In the countercurrent flow, the amine solution and the flue gas come into contact within the absorber. This allows CO₂ to be captured through a chemical reaction between the amine and the gas. Thermal treatment in the stripper column (desorber) regenerates the CO₂ -laden amine stream that exits the absorber bottom. This process, conducted at temperatures ranging from 100°C to 130°C, liberates the captured CO₂. The essential heat for regeneration comes from a reboiler that uses steam from the power plant's water-steam cycle. After heat exchange, the regenerated, lean amine solution returns to the absorber. Finally, the liquefaction of separated CO₂ as a substitute for atmospheric release is a thermochemical process necessitating elevated pressure and reduced temperature conditions. Generally, a pressured chilling technique executes this procedure. A multi-stage compressor first compresses CO₂ gas to the required pressure. A sequence of heat exchangers then cools the high-pressure gas below ambient temperature. Throughout this cooling phase, the internal energy of the gas diminishes, nearing the liquefaction threshold. The partially liquefied carbon dioxide is subsequently directed to a separating tank. The liquid phase and vapor phase are delineated here. The liquid CO₂ is subsequently transferred to cryogenic tanks for storage or transit. Greenhouses acquire liquefied CO₂ to augment crop production. CO₂ is an essential element of photosynthesis and vital for plant growth. Due to its significant impact

on plant growth and yield, CO₂ enrichment has gained substantial importance in controlled-environment agriculture. Implementing enrichment at appropriate levels within greenhouses can enhance crop productivity (Tezcan et al., 2011).

Aqueous MEA solution is currently the industry-standard solvent for gas streams with low CO₂ concentrations. This is particularly advantageous for low-pressure gas treatment scenarios demanding high CO₂ removal efficiency. MEA/water solutions offer several key benefits, including their high reactivity with CO₂, substantial absorption capacity, and favorable low molecular weight. However, a significant drawback of MEA-based systems is the high heat produced by the reaction between MEA and CO₂. This situation increases the stripping process's energy requirements (Cifre et al., 2009).

Syngas, devoid of CO₂, is introduced into the drying unit to extract water vapor from the gases using a mist holder mechanism. Wet gases can cause corrosion in pipelines and other equipment. For this reason, the drying process is of enormous importance.

Syngas enter the Pressurized Swing Adsorption (PSA) unit to separate CO₂ and CH₄ from CO and H₂. The PSA unit is composed of an adsorption bed and an adsorbent material. In the gas mixture, the adsorbent tends to bind to a specific gas molecule. The PSA unit's working principle is to alternately flow the gas mixture between the adsorbent beds using high pressure, enabling the adsorbent to absorb and release gas molecules. A dual-stage PSA configuration was implemented for enhanced separation efficacy relative to a standalone PSA process. This system comprises two cascaded PSA cycles, PSA I and PSA II. PSA I's job is to make a raffinate stream that is high in the lighter component and an extract stream that is high in the heavier component. The extract stream from PSA I is then sent to PSA II to be cleaned even more. The final light product recovered from PSA II is then combined with the incoming feed and introduced into PSA I to complete the cyclical process (Delgado et al., 2021).

A buffer tank receives the product gas stream, a mixture of CO and H₂ that exits PSA II. The system uses 20% of this stored syngas as fuel for its natural gas-powered pyrolysis process, and sells the remaining 80% to industrial zone companies to meet their natural gas needs. The use of gas supplied to industrial areas has been included within the system boundaries.

CO₂ and CH₄ gases exit the PSA I unit and enter the membrane unit for separation. The method for membrane separation relies on different gases passing through the membrane at varying speeds.

Pressure-driven membrane separation is a promising technology for CO₂ capture from syngas. This method feeds high-pressure syngas into a polymeric membrane, which is more resistant and less reactive, allowing CO₂ to permeate rapidly. The separated gases are then collected as low-pressure streams, while CH₄ is discharged from the other side of the membrane (Baker, 2002).

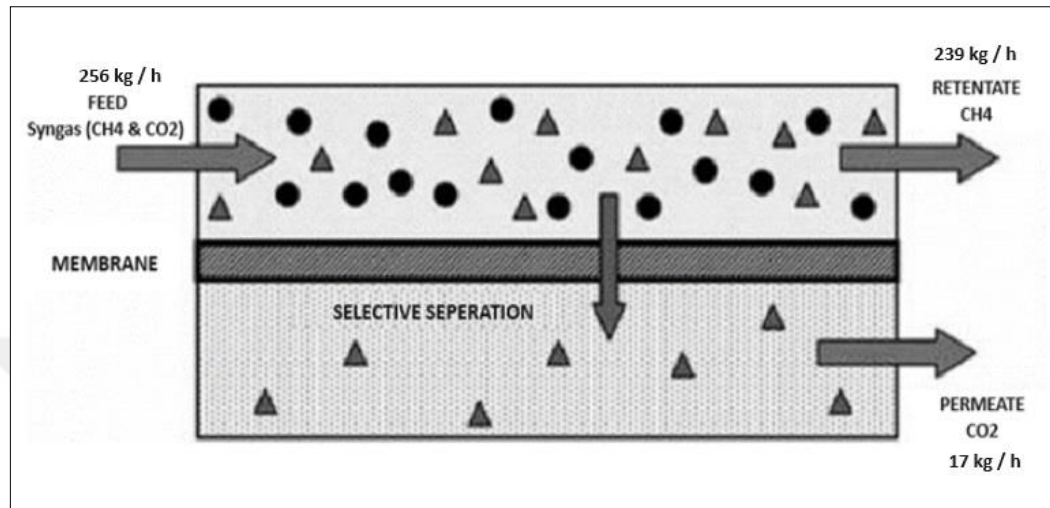


Figure 3.5. Pressure driven membrane.

The liquefaction unit uses a cascade system to direct the extracted methane gas from the membrane system, facilitating its storage and transportation. Reducing the volume of liquefied methane enables transportation to regions inaccessible by pipeline, particularly across seas. Salih Coşkun (2004) conducted an analysis which revealed that the total power consumption required for natural gas liquefaction (pumps and compressors) accounts for approximately 3.4% of the equivalent power of liquefied methane. The system's pumps and compressors expend the total power during methane liquefaction. Green methane, which contributes to reducing greenhouse gas emissions, can be injected into the natural gas grid or used as fuel in transportation (Byun & Han, 2022). The consumption of the obtained LNG has been included within the system boundaries.

In the second scenario, depicted in Figure 3.6, the amine scrubber unit generates electricity using a gas engine instead of producing LNG. Syngas undergoes combustion when it enters the gas engine. The engine converts the resulting heat energy into mechanical energy, which the generator then converts into electrical energy. A heat exchanger simultaneously transfers the released heat during combustion to water or another fluid, generating usable heat. The electricity grid directly receives the generated electricity. The waste heat can also be utilized for space heating, hot water production, greenhouse heating, and seed germination (Dincer & Erdemir, 2021).

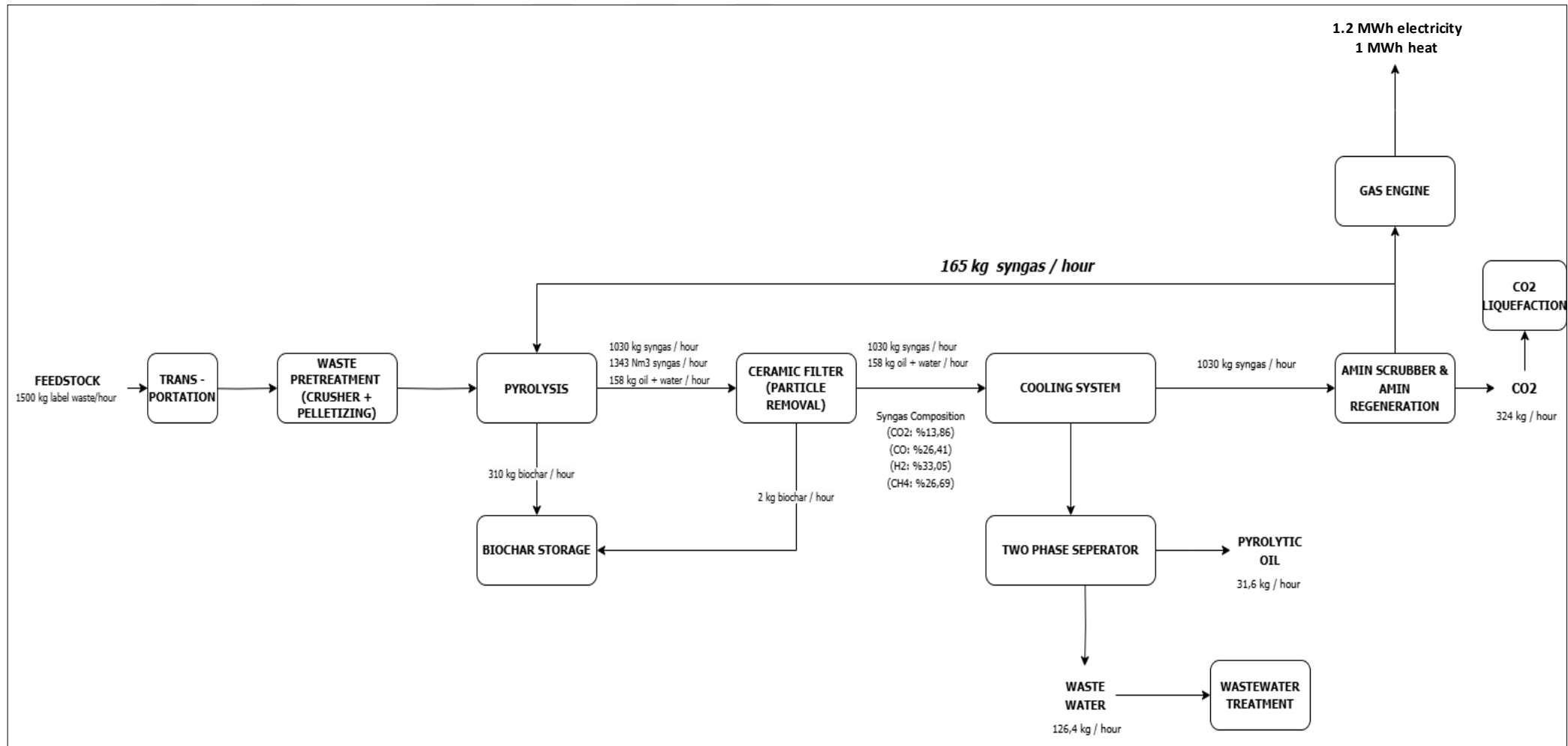


Figure 3.6. The schematic diagram of alternative scenario.

3.2. Life Cycle Inventory Analysis and Key Assumptions

A life cycle inventory analysis compiles a list of everything that goes into and comes out of a product throughout its lifespan, from material extraction to disposal (ISO 14044, 2006). This section will detail all the data collected and calculated for this specific LCI study, along with any estimations made along the way. Whereas Table 3.1. presents all stages, inputs, and resources for both current and alternative scenarios, Table 3.2 shows the values of all input data and their expressions in GaBi. To facilitate exposition, each stage (S) of the operation has been assigned a numerical designation. Henceforth, these numbers will be employed for reference.

The study relied on a set of assumptions regarding gas and input storage, and pump energy consumption during specific process phases and under defined conditions. This assumption led to the prediction that pumps and storage could account for up to 10% of the total system energy. S14 will provide a detailed explanation of these energies.

Table 3.1. The inventory data sources for stages.

LCA Phase Definition	Operation	Stage	Required Data	Data Sources
Raw Material Extraction	Raw Material Transportation	S0; Transportation	Fuel Consumption	GaBi 8.0 software, Market Research
Manufacturing	Waste pretreatment	S1; Crushing & Pelletizing	the amount of label waste usage, electricity consumption for waste pretreatment	GaBi 8.0 software, ITU Sentek, Market Research
	Pyrolysis	S2; Pyrolysis	Feedstock consumption, the amount of syngas consumption	ITU Sentek, GaBi 8.0 software
		S3; Biochar Deposition	Biochar released from pyrolysis and ceramic filter	ITU Sentek, GaBi 8.0 software
Use	Product and by Product utilization	S5; Cooling System	The amount of syngas and liquid released from ceramic filter, the amount of electricity consumption for chiller	ITU Sentek, GaBi 8.0 software, Market Research
		S6; Two Phase Separator	The amount of electricity consumption of two phase separator	ITU Sentek, GaBi 8.0 software, Market Research
		S8; Amin scrubber & Amin regeneration	The amount of syngas released after cooling, the amount of MEA usage, the amount of natural gas required in amin scrubber	ITU SENTEK, GaBi 8.0 software, Scientific paper (Cifre et al., 2009),
		S9; CO ₂ Liquefaction	The amount of adsorbed CO ₂ at amin scrubber, electricity consumption for CO ₂ liquefaction	ITU SENTEK, GaBi 8.0 software, (Yoo et al., 2013)
		S10; Pressure Swing Adsorption	The electricity consumption of compressor and fan, the amount of syngas entering compressor	Market Research, ITU SENTEK, GaBi 8.0 software
		S11; Syngas deposition	The electricity consumption of fan, amount of syngas released from PSA	Market Research, ITU SENTEK, GaBi 8.0 software
		S12; Methane Liquefaction	The amount methane released from CH ₄ & CO ₂ separation unit, the amount of electricity consumption for CH ₄ liquefaction	ITU SENTEK, GaBi 8.0 software, Scientific paper (Coşkun, 2004)
		S13; Gas Engine	The amount of syngas released from Amin Scrubber, gas engine efficiency	ITU Sentek, GaBi 8.0 software, Market Research
		S14; Energies for pump and gas storage	The energy consumed by the entire process	ITU Sentek, GaBi 8.0 software, Market Research, Scientific papers (Sadik, 2019) and (Cifre et al., 2009), (Coşkun, 2004)
End of Life Facilities	Waste Emission & Utilization	S4; Removal of Particles	Electricity consumption for ceramic filter, the amount of generated syngas, liquid and residual biochar from pyrolysis	ITU Sentek, GaBi 8.0 software, Market Research
		S7; Wastewater Treatment	The amount of generated wastewater, electricity consumption for electrocoagulation	ITU SENTEK, GaBi 8.0 software, Scientific paper (Sadik, 2019)

Table 3.2. Inventory table.

LCA Phase	Operation Stage	Substage	Input Data	Value	Output Data	Value
Raw Material Extraction	Raw Material Transportation	Transportation	Diesel	32 L / 10 km	-	-
Manufacturing	Waste Pretreatment	Waste Pretreatment (Crushing)	Electricity	30 kWh / 1500 kg feedstock	Feedstock	1050 kg / hour
		Waste Pretreatment (Pelletizing)	Electricity	50 kWh / 1500 kg feedstock	Feedstock	1050 kg / hour
	Pyrolysis	Pyrolysis	Feedstock	1050 kg / hour	Syngas	1030 kg / hour
			Syngas	80 kg / hour	Liquid	158 kg / hour
					Biochar	312 kg / hour
Use	Biochar Deposition	Biochar Deposition	Biochar	312 kg / hour	Biochar	312 kg / hour
End of Life Facilities	Removal of Particle	Ceramic Filter	Electricity	1.5 kWh / syngas	Syngas	1030 kg / hour
			Syngas	1030 kg / hour		
			Liquid	158 kg / hour	Liquid	158 kg / hour
			Biochar	2 kg / hour	Biochar	2 kg / hour
Use	Cooling System	Chiller & Heat Exchanger & Gas Liquid Separator	Syngas	1030 kg/hour	Syngas	1030 kg / hour
			Liquid	158 kg / hour	Liquid	158 kg / hour
			Electricity	25 kWh/syngas		
	Two Phase Separator	Separation of wastewater and pyrolytic oil	Liquid	158 kg / hour	Pyrolytic oil	31.6 kg / hour
			Electricity	20 kWh / pyrolytic liquid	Waste water	126.4 kg / hour
End of Life Facilities	Wastewater Treatment	Electrocoagulation	Wastewater	126.4 kg / hour	Treated waste water	126.4 kg / hour
			Electricity	15.9 kWh / m ³ wastewater		
Use	Amin scrubber	CO ₂ Adsorption and Desorption	Syngas	1030 kg/hour	CO ₂ gas	324 kg / hour
			Natural Gas	36,81 m ³ /hour	Syngas	706 kg / hour
			MEA	2 kg/1 tCO ₂		
	CO ₂ Liquefaction	CO ₂ Liquefaction	Electricity	115kWh/1 tCO ₂	Liquid CO ₂	324 kg / hour
			CO ₂	324 kg/hour		
	Pressure Swing Adsorption	Separation of H ₂ & CO from CH ₄ & CO ₂	Syngas	706 kg/hour	Syngas (CO ₂ & CH ₄)	256 kg / hour
			Electricity	52.2 kWh / syngas	Syngas (CO & H ₂)	450 kg / hour
	Syngas deposition	Syngas released from PSA unit	Syngas	450 kg / hour	Syngas / Off gas (for other industries)	309.02 kg / hour
					Syngas (for pyrolysis process)	140.97 kg / hour
		Fan Electricity Demand	Electricity	0.55 kWh / syngas	-	-
	Methane Liquefaction	CO ₂ &CH ₄ gas separation	Methane	239 kg/h	CO ₂ gas	17 kg / hour
					CH ₄ gas	239 kg / hour
		Methane Liquefaction	Electricity	%3.4 total energy consumed for liquefaction/liquefied natural gas amount	Green LNG	239 kg / hour

First of all, it is assumed that the 1500 kg of label waste arriving daily comes from a waste collection facility 10 km away. The fuel consumption of the diesel truck carrying this waste, which makes one trip per day, is assumed to be 32 lt/100 km. Based on this assumption, the daily diesel consumption for transportation is calculated as $((32 \text{ lt}/100 \text{ km}) * (10 \text{ km}/\text{day}))$ 3.2 lt/day.

The greenhouse gas emissions caused by this transportation are calculated and entered into the system as output with respect to the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). After using the data in Table 3.3, 0.3542 kg CO₂/hour transport-related emissions were found.

$$\begin{aligned} \text{CO}_2 \text{ released from diesel truck} = \\ \text{Diesel consumption} * \text{CO}_2 \text{ Emission Factors} * \text{Net Calorific Value} * \\ \text{Global Warming Potential} \end{aligned} \quad (3.1)$$

Table 3.3. Emission factor and net calorific value for diesel oil.

Fuel	Gas	CO₂ Emission Factors (kg/TJ)	Net Calorific Value (TJ/GG)	Global Warming Potential
<i>Diesel Oil</i>	CO ₂	74100	43	1
	CH ₄	3.90		25
	N ₂ O	3.90		298
<i>Natural gas</i>	CO ₂	56100	48	1
	CH ₄	1.0		25
	N ₂ O	0.1		298
<i>Liquid Natural Gas</i>	CO ₂	64200	44.2	1
	CH ₄	3.0		25
	N ₂ O	0.60		298

Before entering the pyrolysis process, label waste undergoes a two-stage pretreatment. In the first stage, the waste fed into a machine called the crushing system is broken down into smaller pieces. This process consumes 30 kWh of energy. After crushing, the pelletizing process homogenizes the waste and prepares it for feeding into the pyrolysis reactor. This process also requires 50 kWh of energy. The energy required in waste pretreatment has been identified through market research.

The pyrolysis system operates using a two-stage feeding procedure. In the initial stage, 46 kg of natural gas are utilized for approximately 3 hours to initiate the system. This allows the reactor to reach the desired temperature (850 °C) and commence pyrolysis.

Following this three-hour initialization phase, the system operates on its own syngas. In the process in question, natural gas was disregarded as an input since it was initially used for start-up purposes only, and the process can generate its energy in the later stages. This syngas is composed of CO and H₂ gases with a calorific value of 11.5 MJ/Nm³. To sustain pyrolysis, the system requires 80 kg of syngas per hour.

After completing the pyrolysis process, the system produces 1030 kg of syngas, 158 kg of liquid (an oil-water mixture), and 312 kg of carbon-enriched biochar per hour. Detailed information regarding the biochar is presented in Table 3.2. Pyrolysis produces 312 kg/hour, whereas the ceramic filter produces 3.12 kg/hour. The details of the energy consumption required for biochar storage are not provided in S3. Given this missing information, all storage energies are presented as estimates in S14.

During pyrolysis, syngas, liquids, and biochar enter the ceramic filter. At this stage, approximately 1% of the biochar sent to storage is assumed to pass through the ceramic filter. This biochar passing through the ceramic filter is returned to the biochar deposition unit with a 1.5 kWh energy-consuming fan. Thanks to this high-efficiency ceramic filter operating at 400 °C, the syngas are purified and cleaned of particles.

In stage 5, the gas and liquid mixture exiting the ceramic filter has two components that need to be cooled and separated before syngas processing. For this purpose, 200 liters of water are cooled using a 25 Kw chiller and brought into contact with the gas and liquid flow in the heat exchanger. Water consumption in the cooling process is disregarded, as the water circulates and can be reused. The cooled gas and liquid mixture enters the gas-liquid separator, where the two phases are separated. The separated liquid is sent to the two-phase separator, while the gas passes on to the amine scrubber unit at its flow rate. As a result of this process, the syngas have reached the desired temperature (25 °C) and purity.

In stage 6, a liquid stream of 158 kg/h of oil and wastewater enters a two-phase separator after separating from a gas-liquid separator. This separator divides the stream into two phases: 80% wastewater (126.4 kg/h) and 20% pyrolytic oil (31.5 kg/h). For this separation process, the separator

uses 20 kWh of electrical energy. The calorific value of pyrolytic oil, which contains various organics and aromatics, is approximately 7000 kcal/kg. This pyrolytic oil can be refined into a valuable resource for the biofuel industry (Hasan et al., 2023).

In stage 7, wastewater discharged from the two-phase separator is treated using the electrocoagulation unit located within the facility. In this method, electrocoagulation is employed to aggregate and precipitate water contaminants, effectively removing them from the water. Due to the unknown composition of the discharged wastewater, a thorough literature review was conducted. Based on the findings of this review, which considered the high levels of COD, turbidity, suspended solids, and the volume of discharged wastewater, the electrocoagulation method was selected as the most suitable treatment option (Sadık, 2019). This approach effectively removes approximately 98% of COD, enabling the treated water to be discharged into the municipal water supply system. Calculations of the energy consumption of the pumps used for treatment and transportation are presented in Stage 13. Under optimal conditions, wastewater treatment using electrocoagulation with iron (Fe) consumes 15.9 kWh/m³. Therefore, to treat the 0.12 m³/h wastewater entering the process (0.12 m³/h * 15.9 kWh/ m³), 1.90 kWh of electricity is consumed.

After cooling the system, syngas enters the amine scrubber unit. The regeneration of a CO₂-saturated amine solution entails a substantial energy expenditure. This energy requirement can be dissected into three primary components. Firstly, energy is employed to counteract the desorption enthalpy, which is directly associated with absorption heat during CO₂ capture. Secondly, the amine solution must be elevated to its boiling temperature. Finally, energy is employed to vaporize water by stripping steam. Literature has documented an energy demand for MEA ranging from 3.9 to 4.2 MJ/kg of captured CO₂ (Cifre et al., 2009). Assuming an energy demand of 4 MJ/kg CO₂ for MEA in this particular scenario and a CO₂ capture rate of 324 kg/hour, the total energy demand for the amine scrubbing unit can be calculated as 4 MJ/kg CO₂ * 324 kg CO₂ /hour = 1296 MJ/hour. This energy consumption is met by natural gas. Since it is met by natural gas, dividing this amount by the calorific value of natural gas (1296 MJ/h ÷ 35.2 MJ/m³ (IPCC, 2006)) reveals a natural gas consumption of 36.81 m³/hour. The greenhouse gas emissions caused by this natural gas consumption were calculated using the IPCC methodology (IPCC, 2006).

$$\begin{aligned}
 &CO_2 \text{ released from natural gas} = \\
 &\text{Natural gas consumption} * CO_2 \text{ Emission Factors} * \text{Net Calorific Value} * \\
 &\quad \text{Global Warming Potential}
 \end{aligned}
 \tag{3.2}$$

According to the calculations using the values in Table 3.2, CO₂ emissions must be 99.24 kg/hour for MEA to retain the CO₂ in the syngas.

In addition, according to a survey conducted by Rosenthal et al. (2020), it was determined that 2 kg of MEA is required to capture one ton of CO₂. Therefore, as shown in Table 3.2., 0.648 kg/h of MEA is used, calculated as (324 kg CO₂ captured/hour * 2 kg MEA/ton captured CO₂).

Water consumption calculations are disregarded because the water used in the CO₂ capture process within the MEA solution can be recycled and purified repeatedly. Stage 13 will provide an estimate of the amount of electricity required to compress captured CO₂ for pipeline transport to a storage site.

In order to prevent the release of 324 kg/hour of captured CO₂ into the atmosphere, a liquefaction process was implemented. According to Yoo et al. (2013), the energy required for liquefaction is 115 kWh/t CO₂. Therefore, the energy consumption for this process is (324 kg CO₂/hour * 115 kWh/t CO₂) = 37.26 kWh.

Following CO₂ removal in the amine scrubber unit, the syngas are directed to the drying unit. At stage 10, mist eliminators remove water vapor from the gas. Since mist eliminators operate passively and do not require energy consumption, no separate energy input is shown for the drying process.

After drying, the syngas are transported to a buffer tank using a 2.5 kWh fan. A 50-kWh compressor transfers the syngas from the buffer tank to the PSA unit. When the syngas goes into the PSA unit under high pressure, it is split into two separate gas streams using special adsorbents. One stream has H₂ and CO in it, and the other has CO₂ and CH₄.

In stage 11, the PSA unit produced syngas with a flow rate of 450 kg/hour, a density of 0.32 kg/Nm³, and a volume of 798 Nm³/hour, which was then transferred to the buffer tank. This syngas has a composition of 44.4% CO and 55.6% H₂. 20% of this syngas is used as an energy source for pyrolysis in the facility, which has a 0.55 kWh fan. The remaining 80% is employed as a natural gas source in different facilities. The calculation method presented below determines the natural gas equivalent of these syngas, which be used in different facilities.

$$\begin{aligned} \text{Natural Gas Equivalent} \left(\frac{\text{Nm}^3}{\text{hr}} \right) = & \frac{\text{Syngas Volume} \left(\frac{\text{Nm}^3}{\text{hr}} \right) *}{\left(\frac{\text{Syngas Heating Value} \left(\frac{\text{MJ}}{\text{Nm}^3} \right)}{\text{Natural Gas Heating Value} \left(\frac{\text{MJ}}{\text{Nm}^3} \right)} \right)} \end{aligned} \quad (3.3)$$

$$\text{Natural Gas Heating Value} = 35.2 \frac{\text{MJ}}{\text{Nm}^3} \quad (\text{IPCC, 2006}) \quad (3.4)$$

$$\text{Natural Gas Equivalent} \left(\frac{\text{Nm}^3}{\text{hr}} \right) = \frac{\left(\frac{798 \text{ Nm}^3}{\text{hr}} * 0.70 * \frac{11.5 \text{ MJ}}{\text{Nm}^3} \right)}{\frac{35.2 \text{ MJ}}{\text{Nm}^3}} = 182.5 \frac{\text{Nm}^3}{\text{hr}} \quad (3.5)$$

The use of 182.5 Nm³/hour natural gas causes greenhouse gas emissions of 319.75 kgCO₂/hour.

In the LNG liquefaction stage, a syngas containing 2.5% CO₂ and 97.5% CH₄, with a volumetric flow rate of 371 Nm³/h and a density of 0.69 kg/Nm³, was separated using PDM technology. In this method, the syngas enters the Pressure Driven Membrane (PDM) under high pressure from the PSA unit, and CH₄ and CO₂ are separated. No additional energy is required during this process. This is because the pressure from the compressor, which the syngas passes through before the PSA unit, can also be used in the PDM process. Because of the separation process, 17 kg/h of CO₂ is released into the atmosphere, while 239 kg/h of methane is liquefied using pumps and compressors.

According to Salih Coşkun (2004), the energy used in LNG production accounts for approximately 3.4% of the energy obtained from liquefied methane. According to ITU SENTEK data, 239 kg/h (358 Nm³/h) of LNG was obtained as a result of liquefaction. For this reason, the energy consumed for this liquefaction is stated below.

$$\text{Energy consumed} = \text{LNG generated} * \%4 * \text{calorific value of LNG} \quad (3.6)$$

$$\text{calorific value of LNG} = 10.54 \frac{\text{kWh}}{\text{m}^3} \quad (\text{Forest Research, 2022}) \quad (3.7)$$

$$\begin{aligned} \text{Energy consumed for methane liquefaction} = & 358 \frac{\text{Nm}^3}{\text{hour}} * \%4 * 10.54 \frac{\text{kWh}}{\text{m}^3} = 128 \text{ kWh} \end{aligned} \quad (3.8)$$

When the data in Table 3.3 is used, 680.87 kg CO₂/hour greenhouse gas emissions occur due to LNG use.

$$\begin{aligned} CO_2 \text{ released from Liquid Natural Gas} = \\ LNG \text{ consumption} * CO_2 \text{ Emission Factors} * \\ Net \text{ Calorific Value} * Global \text{ Warming Potential} \end{aligned} \quad (3.9)$$

An alternative process presents a scenario within the scope of integrating a gas engine with a cogeneration unit. The alternative scenario includes the first nine stages: the gas engine (13. Stage) and the energies for pump and gas storage (14. Stage). In the 13. Stage of this scenario, 1.2 MWh of electricity and 1 MWh of thermal energy are produced using syngas (706 kg/hour–1166 Nm³/hour) purified from CO₂ by the amine scrubber. The values of 1.2 MWh of electricity and 1 MWh of thermal energy were calculated based on the Jenbacher JMS 420 GS-S.L. catalog.

The amount of NO_x and CO₂ released during the cogeneration process is included in the following calculation.

$$NO_x \text{ Emission Value} = 500 \frac{mg}{Nm^3} * The \text{ amount of syngas entering gas engine} \quad (3.10)$$

$$NO_x \text{ Emission Value} = 500 \frac{mg}{Nm^3} * 1166 \frac{Nm^3}{hour} = 583 \text{ kg } \frac{NO_x}{hour} \quad (3.11)$$

$$CO_2 \text{ Emission Value} = \frac{(Fuel \text{ Consumption} * CO_2 \text{ Emission Factor})}{Cogeneration \text{ Efficiency}} \quad (3.12)$$

$$\begin{aligned} CO_2 \text{ Emission Factor} = \\ 2.04 \frac{kg CO_2}{Nm^3 \text{ natural gas}} \text{ (Department for Energy Security and Net Zero, 2023)} \end{aligned} \quad (3.13)$$

$$CO_2 \text{ Emission Value} = \frac{\left(1166 \frac{Nm^3}{hour} * \frac{2.04 \text{ kg } CO_2}{Nm^3 \text{ natural gas}} \right)}{79.5\%} = 2992 \text{ kg } \frac{CO_2}{hour} \quad (3.14)$$

In the alternative scenario, the energy requirement of the pyrolysis system is met by 15% of the syngas it produces.

Stage 14 within the system, pumps and gas storage components were estimated for the current and alternative scenarios. This estimation was made based on market research and accounted for 10% of the total energy consumption in the system. Therefore, 43.83 kWh and 25.74 kWh of energy were expended for pumps and gas storage in the current and alternative scenarios, respectively. This energy consumption was modeled as an input to the pyrolysis stage in the GaBi program.

The products resulting from both scenarios are given in Table 3.4.

Table 3.4. Products from scenarios and baseline method.

Product	Current Scenario	Alternative Scenario	Baseline Method
<i>Carbon-rich biochar</i>	312 kg/h	312 kg /h	-
<i>Pyrolytic oil</i>	31.5 kg /h	31.5 kg /h	-
<i>Treated wastewater</i>	126.4 kg /h	126.4 kg /h	-
<i>Liquified CO₂</i>	324 kg /h	324 kg /h	-
Green LNG	239 kg /h	-	-
Offgas (Natural gas equivalent)	548 Nm³/h (182.5 Nm³/h natural gas equivalent)	-	-
<i>Energy</i>	-	1.2 MWh Electricity & 1 MWh Heat	2.39 MWh Electricity

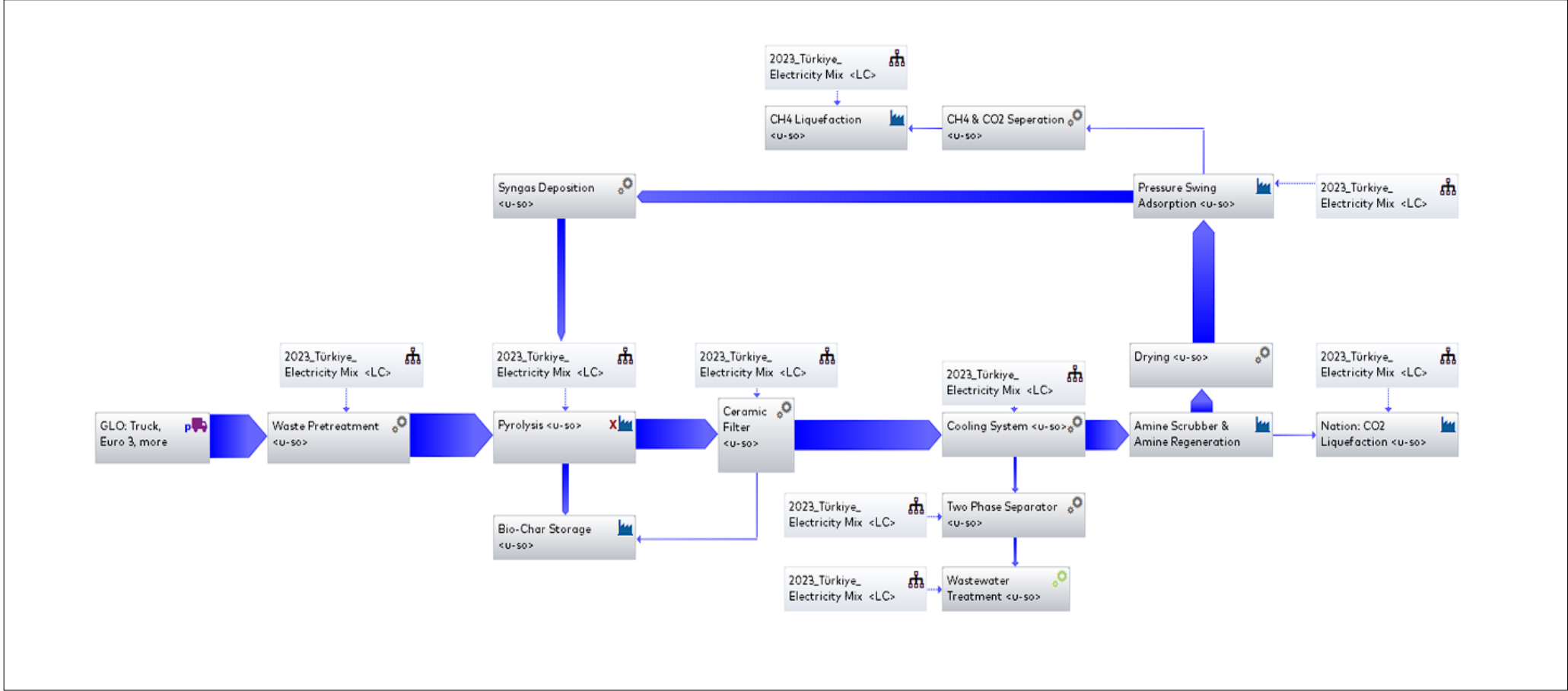


Figure 3.7. Life cycle flow chart for current scenario in GaBi.

3.3. Incineration Method for Label Waste

The evaluation of the combustion process of label waste encompasses system boundaries that include the transportation of labeled waste to the designated incineration facility, the crushing and pelletizing processes, and incineration, as illustrated in Figure 3.9. The process referred to as incineration involves several stages. First, organic compounds react with oxygen to form carbon dioxide and water. Next, the high temperature and waste gases generated are used to boil water and produce steam in a Waste Heat Boiler. This steam is then converted into mechanical energy via a steam turbine, which is further transformed into electricity through a generator. To ensure that the waste gases are properly cleaned before being released into the environment, a gas cleaning unit is employed. In this unit, the gases are cooled, purified of acidic compounds, and solid particles are filtered. The ash generated from the incineration of waste can be utilized in the construction industry as an additive in concrete production. The related processes are shown in Figure 3.10.

In the baseline method, a fluidized bed boiler system first utilizes natural gas to heat the system for around 3-5 hours to a temperature of 850-900 degrees. Natural gas used for startups is ignored in the calculations. Subsequently, as a pre-treatment, heat energy is derived from the combustion of label waste that has been subjected to crushing and pelletizing procedures. Fluidized bed boilers are specifically engineered to maximize the interaction between fuel particles and air, facilitating complete and efficient combustion. The air utilized in the system maintains the fuel particles in suspension, enabling them to function like a liquid. This enables fuels of varying sizes and characteristics to combust in a uniform mixture. There is no other valuable product obtained besides energy.

The magnitude of losses is contingent upon the technology employed, the system's scale, the temperature of the waste heat, and a myriad of other variables. A comprehensive literature review on waste heat to electricity conversion posits a general efficiency of 30% (Jouhara et al., 2018). As stated below, the combustion process releases energy of up to 5.75 MJ/kg.

$$\begin{aligned} \text{The energy obtained} = \\ (\text{Calorific value of polymer} * 15\%) * (\text{Calorific value of cellulose} * 85\%) \end{aligned} \quad (3.15)$$

$$\begin{aligned}
 &\text{The energy obtained} = \\
 &\left(15.23 \frac{\text{MJ}}{\text{kg of cellulose}} (\text{Kılıç, 2023}) * 85\% \right) * \\
 &\left(41.57 \frac{\text{MJ}}{\text{kg of polymer}} (\text{Kılıç, 2023}) * 15\% \right) * \\
 &(30\% (\text{Jouhara et al., 2018})) = 5.75 \frac{\text{MJ}}{\text{kg of label waste}}
 \end{aligned} \tag{3.16}$$

$$\begin{aligned}
 &\text{The electricity obtained} = \\
 &5.75 \frac{\text{MJ}}{\text{kg of label waste}} * 1500 \frac{\text{kg of label waste}}{\text{hour}} * \\
 &0.0000002778 \frac{\text{MW}}{\text{MJ}} = 2.39 \text{ MWh}
 \end{aligned} \tag{3.17}$$

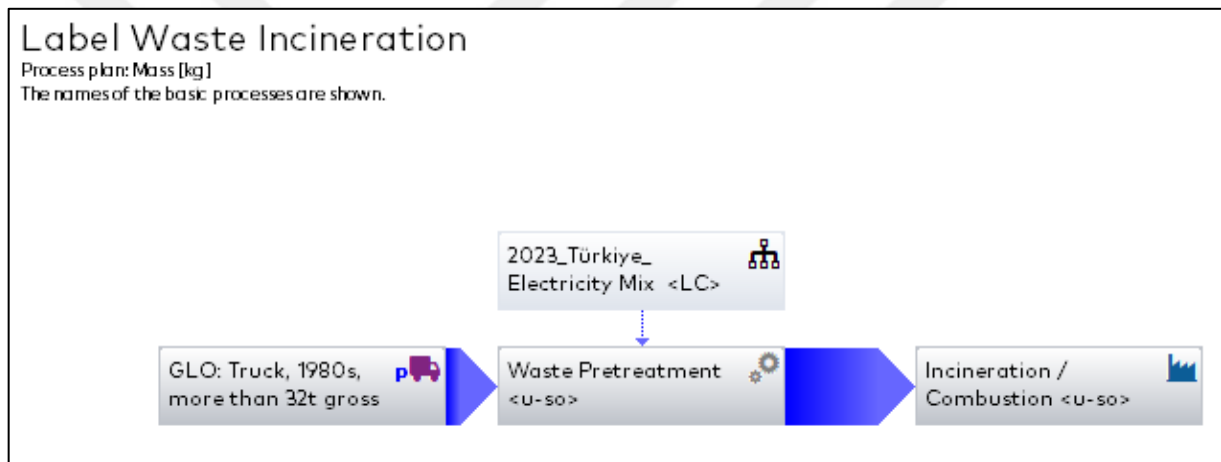


Figure 3.9. Life cycle flow chart for baseline method in GaBi.

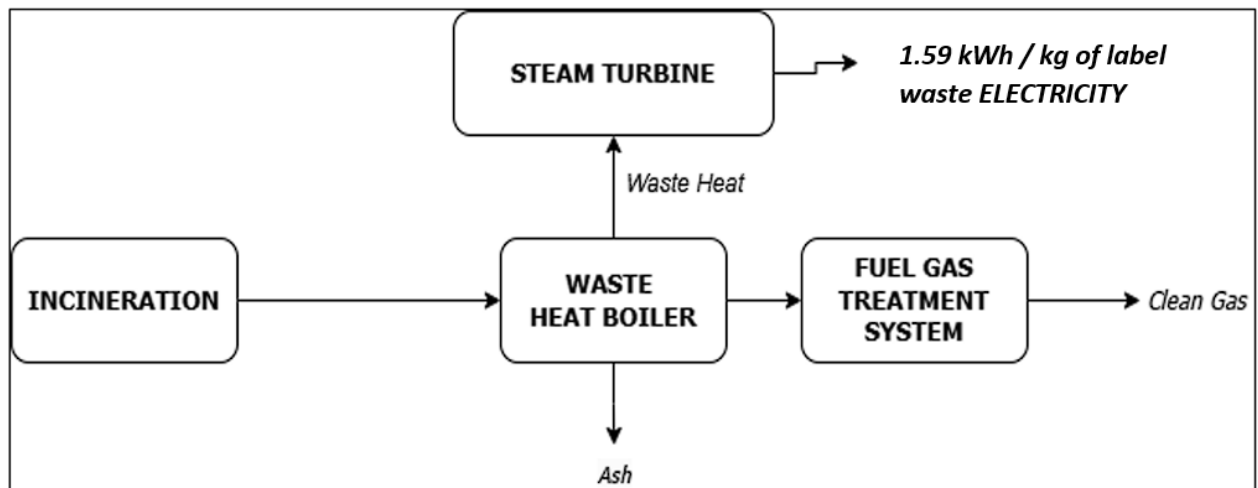


Figure 3.10. The process of incineration of label waste.

4. RESULTS AND DISCUSSION

4.1. Life Cycle Impact Assessment

Life Cycle Impact Assessment emerges as a comprehensive methodology to meticulously scrutinize the potential environmental repercussions of a product or system throughout its entire lifecycle, encompassing all stages from raw material acquisition to final disposal. This holistic evaluation entails a streamlined four-step process: classification, characterization, normalization, and weighting. Classification meticulously arranges the acquired data into designated impact categories, such as climate change, air pollution, and water pollution. Characterization meticulously quantifies each factor's contribution within each impact category and converts them into standardized units. Normalization judiciously compares impact scores to reference values to effectively portray the significance of each impact category. Weighting, an optional step, assigns weights to impact scores to reflect the relative importance of different impact categories (ISO 14044, 2006).

The Institute of Environmental Sciences at Leiden University in the Netherlands developed the CML method. This method utilizes specific indicators to assess environmental impacts across various categories with a thorough application of life cycle stages (Thakkar et al., 2008). As a result, this study uses CML as an LCIA methodology.

The purpose of the first step in life cycle impact assessment, which is classification, is to compare the environmental performance of services or products. In this study, the impact categories are selected as Marine Aquatic Ecotoxicity Potential (MAETP), Global Warming Potential (GWP), Abiotic Depletion (ADP), Human Toxicity Potential (HTP), and Acidification Potential (AP).

Table 4.1. Impact categories and CML 2001 units.

Impact Categories	Unit
<i>Marine Aquatic Ecotoxicity Potential (MAETP)</i>	kg DCB eq.
<i>Global Warming Potential (GWP)</i>	kg CO ₂ eq.
<i>Abiotic Depletion (ADP)</i>	MJ
<i>Human Toxicity Potential (HTP)</i>	kg DCB eq.
<i>Acidification Potential (AP)</i>	kg SO ₂ eq.

4.1.1. Characterization

Characterization transforms raw data collected during the inventory stage into comparable expressiveness, making it meaningful. Consequently, the environmental impacts of different products or services can be demonstrated, and the most significant impact categories can be identified to guide improvement efforts (Guinée , 2002).

A comparative analysis is conducted between the two scenarios and the stages within each scenario. In addition, at the end of the section, the baseline method results will be stated and compared with the current and alternative scenarios. For each impact category, charts are included that show the stages that most impact that category. The impact of the other stages included in the scenarios is shown in Figure 4.6. and Figure 4.7.

4.1.1.1. Abiotic Depletion (ADP). The impacts of the examined scenarios and the stages within these scenarios on the ADP impact category are shown in Figure 4.1. It shows the four stages that most cause abiotic depletion and all other stages of that scenario (pyrolysis, biochar deposition, removal of particles, cooling system, two-phase separator, CO₂ liquefaction, PSA unit, energies for pump and gas storage) for the current scenario and the four stages that most cause abiotic depletion and all other stages of that scenario (cooling system, biochar deposition, removal of particles, two-phase separator, wastewater treatment, gas engine, energies for pump and gas storage) for the alternative scenario. Within the scope of this study, the alternative scenario has a 25% lower abiotic depletion impact than the current scenario. One of the main reasons for this is the higher electricity consumption in the current scenario compared to the alternative.

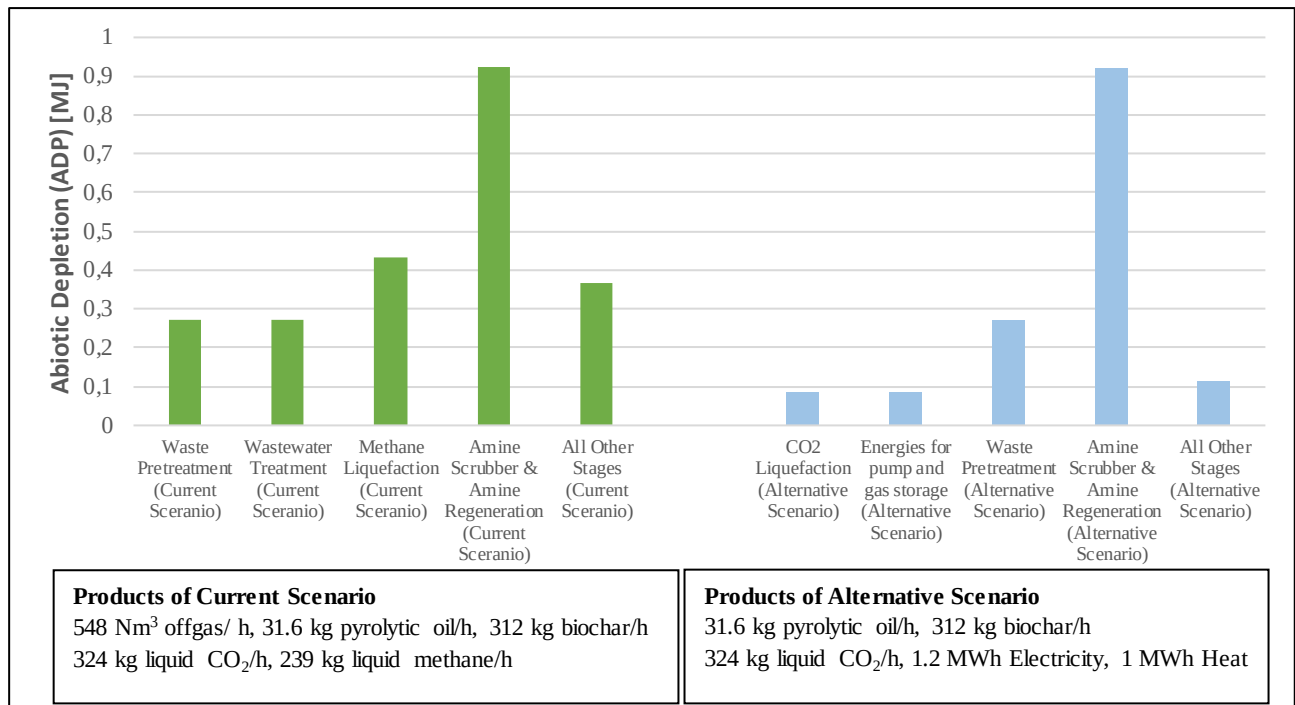


Figure 4.1. Abiotic depletion of scenarios and stages.

In both the current and alternative scenarios, the pyrolysis system is designed to meet its energy demand using the synthesis gas it produces. Life cycle assessments conducted using the GaBi software showed that the use of syngas instead of natural gas resulted in a 55-63% lower abiotic depletion impact in both scenarios.

In 2023, Turkey's electricity generation was derived from a diverse range of sources, with coal (36.3%), natural gas (21.4%), hydropower (19.6%), wind power (10.4%), solar power (5.7%), geothermal power (3.4%), and other sources (3.2%) accounting for the majority of the production (Ministry of Energy and Natural Resources of Turkey, 2024). The significant share of coal and natural gas highlights the prominent role of fossil fuels in Turkey's electricity generation landscape.

In the current and alternative scenarios, the highest electricity consumption is observed in the methane liquefaction stage, leading to a higher level of abiotic depletion in this phase compared to others. The utilization of fossil fuels like coal and natural gas is the primary driver behind this increased consumption.

4.1.1.2. Global Warming Potential (GWP). Figure 4.2. illustrates the impact of the top 3 stages on GWP in both the current and alternative scenarios. It also shows the impact of all other stages, as well as the magnitude of the environmental impact of the stage that reduces GWP in this category. Notably,

the current scenario results in 0.92 kg CO₂-eq GWP, while the alternative scenario has a GWP of 2.76.

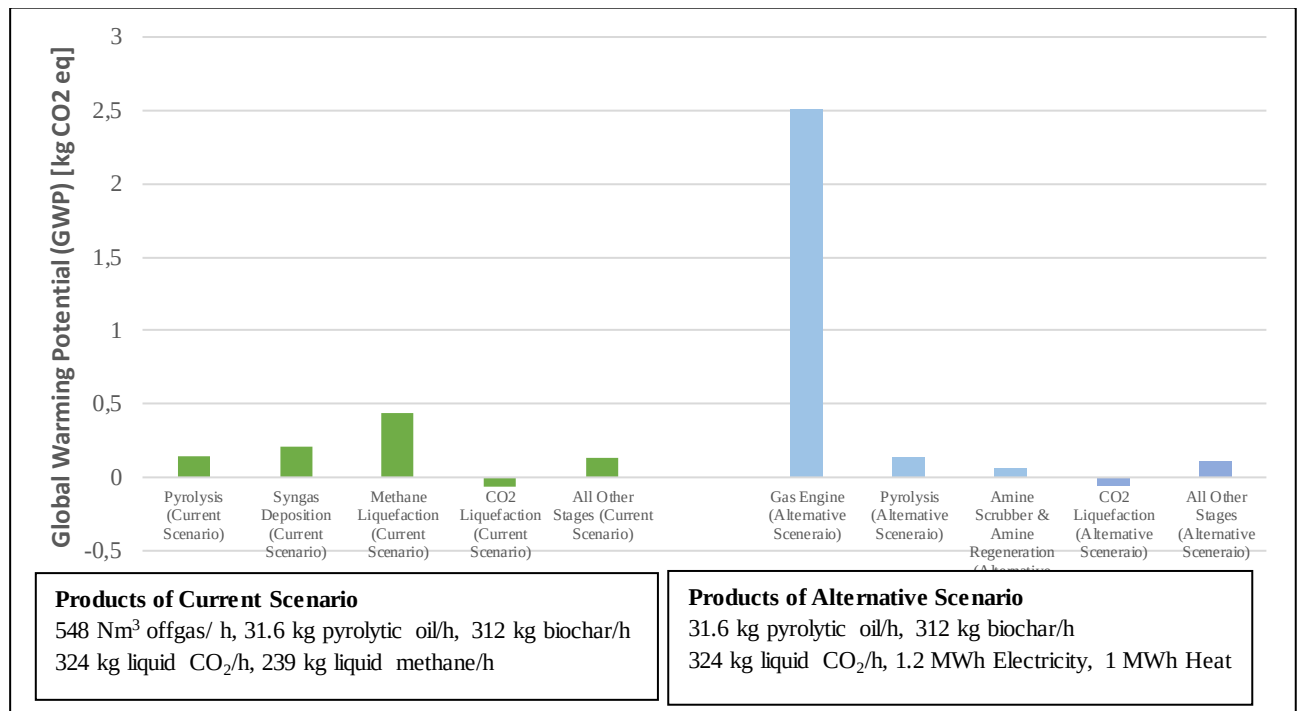


Figure 4.2. Global warming potential of scenarios and stages.

Energy generation using gas engines inevitably leads to greenhouse gas emissions. The combustion process, which forms the basis of the engines' operation, is the primary cause of these emissions. During combustion, fossil fuels react with oxygen to release energy. This chemical reaction releases CO₂, one of the combustion products, into the atmosphere, contributing to global warming by blocking sunlight from reaching the Earth's surface. During combustion, high temperatures cause the dissociation of nitrogen (N₂) and oxygen (O₂) molecules, followed by their recombination to form NO_x. NO_x indirectly contributes to the greenhouse effect. NO_x contributes to ozone (O₃) formation by undergoing chemical reactions in the atmosphere (Yılmaz & İlbaş, 2012). In addition, gas engines cannot convert all potential energy into electrical energy. Gas engines lose some of the released energy during combustion as heat. This heat loss reduces energy efficiency and consequently increases CO₂ emissions.

In the alternative scenario, the stages that have the most significant impact on GWP after the gas engine are, in order of decreasing effect, pyrolysis, amine scrubber and amine regeneration, and the remaining stages (waste pretreatment, feedstock transportation, energies for pump and storage, cooling system, two-phase separator, wastewater treatment, and removal of particles). The amine scrubber and amine regeneration stages rank third in magnitude, as 36.81 m³/h of natural gas provides

the energy needed for MEA to capture CO₂. Additionally, the high GWP of methane liquefaction after pyrolysis in the current scenario is attributed to the consumption of 128 kWh of electricity per ton of green LNG. The GWP of the electricity used, which is derived from fossil fuels, contributes to the overall GWP.

In the current scenario, the most significant impact on GWP comes from the liquefaction of methane at 50% and the storage of syngas at 24%. The main reason for this situation is the high amount of CO₂ emissions resulting from the use of 239 kg of LNG per hour obtained during the methane liquefaction process and the release of synthesis gas containing CO and H₂, which is 80% (548 Nm³/h) used as natural gas in different industries, from the PSA unit into the atmosphere. This situation directly affects the global warming potential, creating a negative impact on climate change. However, if a different scenario is to be considered in future studies, it is thought that the system's greenhouse gas potential could be significantly reduced if the CO₂ emissions resulting from the use of LNG and synthesis gas are captured through methods such as liquefaction or capture. This potential improvement can be more clearly demonstrated through detailed engineering work. This potential improvement can be more clearly defined through detailed engineering work.

The amine scrubber and amine regeneration stages effectively capture CO₂ emissions from the syngas, preventing their release into the atmosphere. Instead, the captured CO₂ is directed to a CO₂ liquefaction unit. This approach aims to enhance greenhouse productivity by utilizing the captured CO₂. Consequently, the current and alternative scenarios yielded a GWP of -0.06, indicating a net negative contribution to global warming.

4.1.1.3. Human Toxicity Potential (HTP). Figure 4.3. illustrates the contribution of the first four and other stages to HTP in the current scenario, while the alternative scenario depicts the same contribution. The current scenario's impact on this category is approximately 40% greater than the alternative scenario's. This high rate is primarily related to the current scenario's electricity consumption of 128 kWh for methane liquefaction. In this scenario, methane liquefaction accounts for 37% of this category's impact. The second-largest contributor is the 80 kWh of electricity used for crushing and pelletizing feedstock in waste pretreatment. This is followed by the electricity consumed by the compressor used to introduce synthesis gas into the PSA unit and the electricity consumed to meet the pumping and storage needs of the entire system. The gases contributing to this category are sulfur dioxide (SO₂), nitrogen dioxide (NO₂), and PM generated from the combustion of fossil fuels employed in electricity generation (Turconi et al., 2013). In the alternative scenario, gas engine-powered is the stage that deviates significantly from the current scenario and contributes the

second-highest proportion (23%) to this category. This is attributed to the NO_x gas emissions generated by gas engines utilizing syngas.

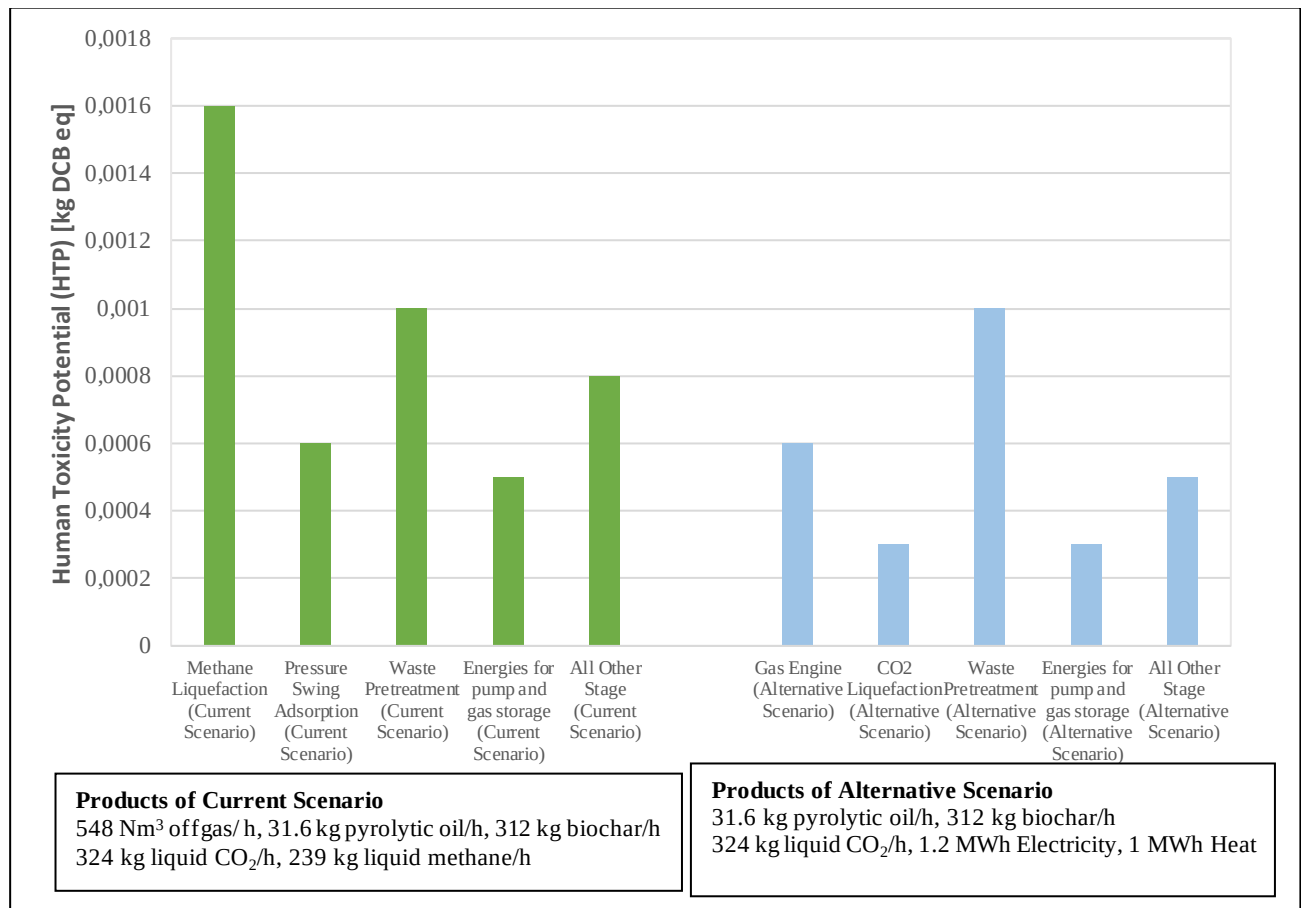


Figure 4.3. Human toxicity potential of scenarios and stages.

4.1.1.4. Marine Aquatic Ecotoxicity Potential (MAETP). As Figure 4.4. illustrates, the current scenario has a significantly greater impact on this category than the alternative scenario, with an increase of approximately 52%. This increase is primarily due to the current scenario's higher electricity consumption, as with HTP. According to Zhang et al. (2019), the effect of electricity on marine aquatic ecotoxicity was found to be more sensitive to diesel, water, and different additives. The various sources used for electricity generation (coal, natural gas, nuclear, etc.) have different environmental impacts. Some of these sources can be combusted, releasing toxic gases and particulates that can mix with seawater. The combustion of coal, a major component of electricity generation, contributes to greenhouse gas emissions, driving climate change, rising sea levels, increasing ocean temperatures, and glacial melting. These alterations disrupt marine environments by destroying the habitats of marine organisms. Moreover, CO₂ emissions from fossil fuels induce ocean acidification, adversely affecting marine life.

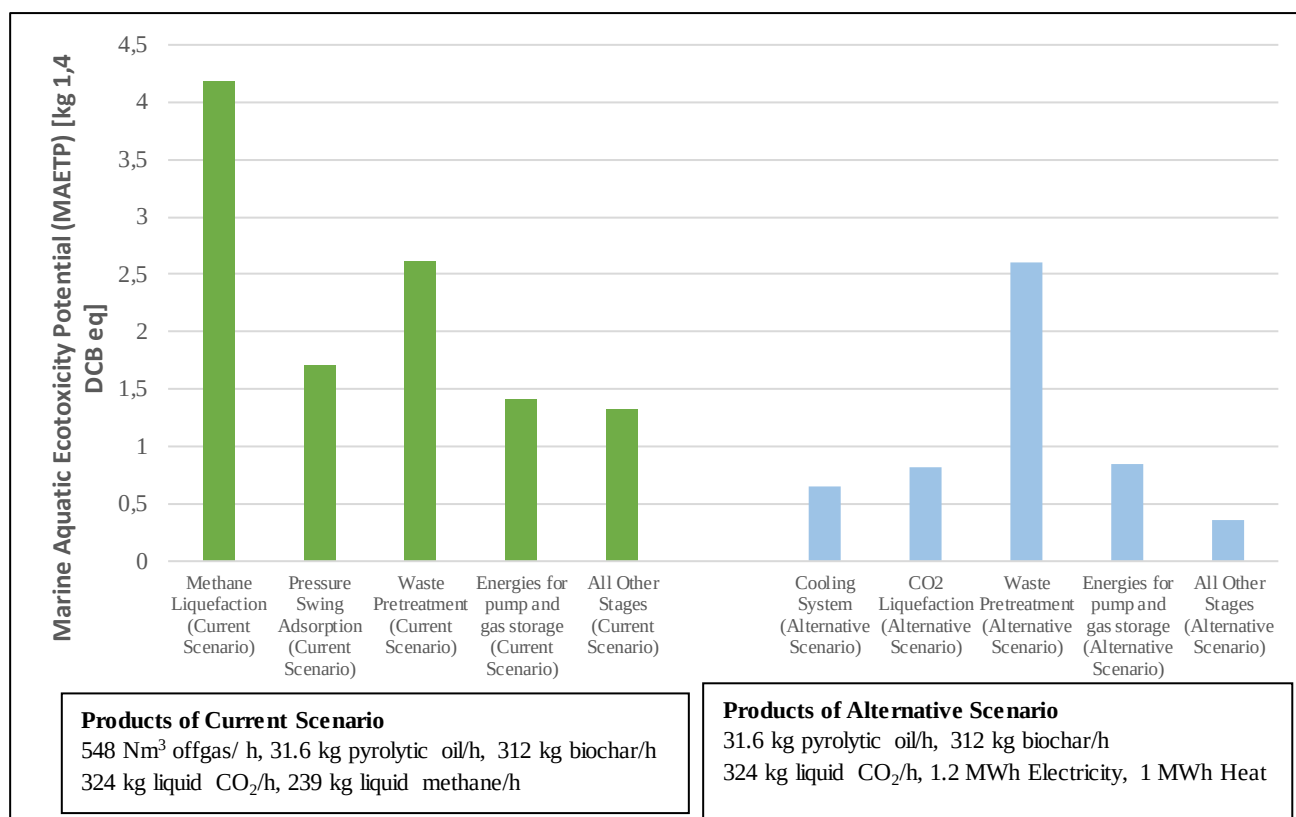


Figure 4.4. Marine aquatic ecotoxicity potential of scenarios and stages.

In the current scenario, the contributions to this category are primarily attributed to methane liquefaction (37.24%), waste pretreatment (23.28%), PSA (15.19%), and energy consumption for pump and gas storage (12.51%), with the remaining stages (11.78%) comprising CO₂ liquefaction, cooling system, two-phase separator, wastewater treatment, and particle removal. Notably, electricity consumption decreases sequentially throughout these stages. In the alternative scenario, as in the current scenario, it was observed that the higher the electricity consumption in a stage, the more it affected MAETP. Wastewater pretreatment (49.51%) was the most significant factor in this category. Pretreatment was followed by energy for pump and gas storage (15.85%), the cooling system (12.38%), and all other stages (6.79%) (Two Phase Separator, Wastewater Treatment, and Removal of Particle, respectively).

4.1.1.5. Acidification Potential (AP). Figure 4.5 illustrates a comparative assessment of the contributions of two distinct scenarios to acidification potential (AP). The gas engine in the alternative scenario releases 583 kg of NO_x per hour, accounting for nearly 56% of the total AP of the scenario. This scenario shows a direct correlation between the atmospheric emissions of acid-forming chemicals, such as nitrogen oxides (NO_x) and sulfur oxides (SO_x), and the potential for acidification. These gases induce acidification in atmospheric, aquatic, and terrestrial ecosystems, disturbing the equilibrium of these environments (Halaszova & Kozlovská, 2021).

Likewise, the elevated electricity demand in processes like the liquefaction of methane and carbon dioxide also contributes to an increase in AP. Fossil fuels produce a significant amount of electricity in this process. The combustion of fossil fuels emits sulfur and nitrogen oxides into the atmosphere, which subsequently react with precipitation to produce sulfuric and nitric acids. In addition, The sulfur in diesel fuel utilized for transporting feedstock is transformed into sulfur dioxide (SO_2) during combustion and emitted into the atmosphere. SO_2 reacts with atmospheric water vapor to produce sulfuric acid. This acid, deposited with precipitation, induces soil acidification, contaminates water supplies, and exerts corrosive effects on both natural and artificial structures.

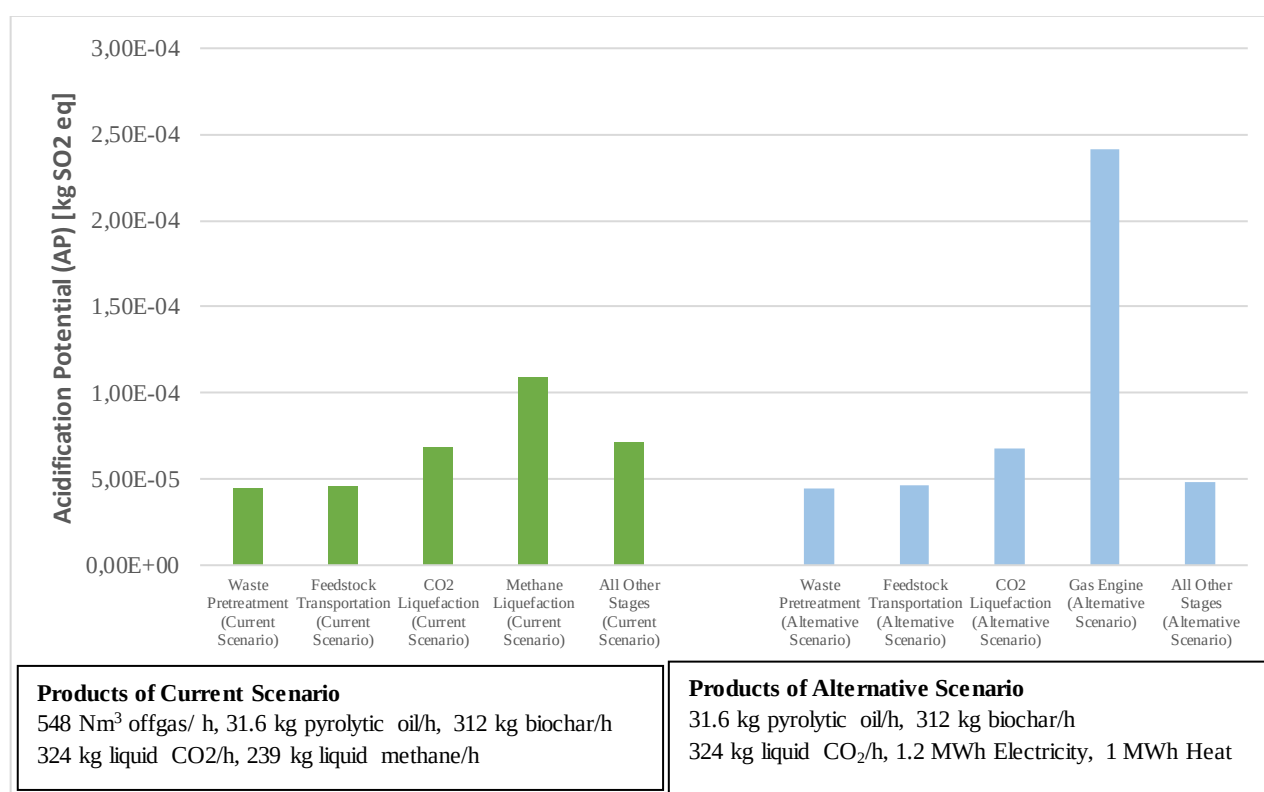


Figure 4.5. Acidification potential of scenarios and stages.

4.1.2. Results of Baseline Method

The life cycle impact assessment results of the incineration (baseline) method, which is the traditional method, are presented in Table 4.2.

Table 4.2. Impact categories' results of baseline method.

Impact Categories	Results
<i>Abiotic Depletion (ADP)</i>	0.27 MJ
<i>Global Warming Potential (GWP)</i>	1.99 kg CO ₂ eq.
<i>Human Toxicity Potential (HTP)</i>	0.0012 kg DCB eq.
<i>Marine Aquatic Ecotoxicity Potential (MAETP)</i>	2.665 kg DCB eq.
<i>Acidification Potential (AP)</i>	0.00015 kg SO ₂ eq.

When evaluating the impact of the incineration scenario on abiotic depletion, it was found to have a 88% lower impact compared to the current scenario and a 81% lower impact compared to the alternative scenario. For the initial phase of the incineration process, only 3-5 hours of natural gas usage is required, and after this period, the label waste ignites spontaneously, eliminating the need for any other energy source. In addition, in the baseline method, there is only the electricity requirement for waste pretreatment, and due to the limited use of natural resources in meeting this need, the impact on abiotic depletion is much lower compared to other scenarios.

When examined in terms of global warming potential, it is observed that the gas engine used for energy production in the alternative scenario leads to a high amount of greenhouse gas emissions. For this reason, the impact of the baseline method on global warming potential is 27% lower compared to the alternative scenario. In the current scenario, the use of 239 kg/h LNG and 548 Nm³/h syngas produced at the end of the process stands out as the processes leading to the highest CO₂ emissions. Although the usage phase of the products is also included in the life cycle assessment, its impact on GWP is 56% less compared to the baseline method.

In the evaluation of toxicity categories, it has been determined that the baseline method has 73% and 76% less impact on human toxicity potential and marine aquatic ecotoxicity potential, respectively, compared to the current scenario, and 55% and 49% less impact, respectively, compared to the alternative scenario. The reason for this difference is that the electricity demand in the baseline method is lower compared to the other scenarios.

The gas engine's emission of 583 kg/h of NO_x increases its impact on acidification potential. When the results are examined, it is understood that the baseline method has 66% less impact on acidification potential compared to the alternative scenario. In the current scenario, especially the sulfur and nitrogen oxides released during the production of electricity used for methane liquefaction,

increase the acidification potential. The impact of the baseline method on acidification potential is 55% less compared to the current scenario.



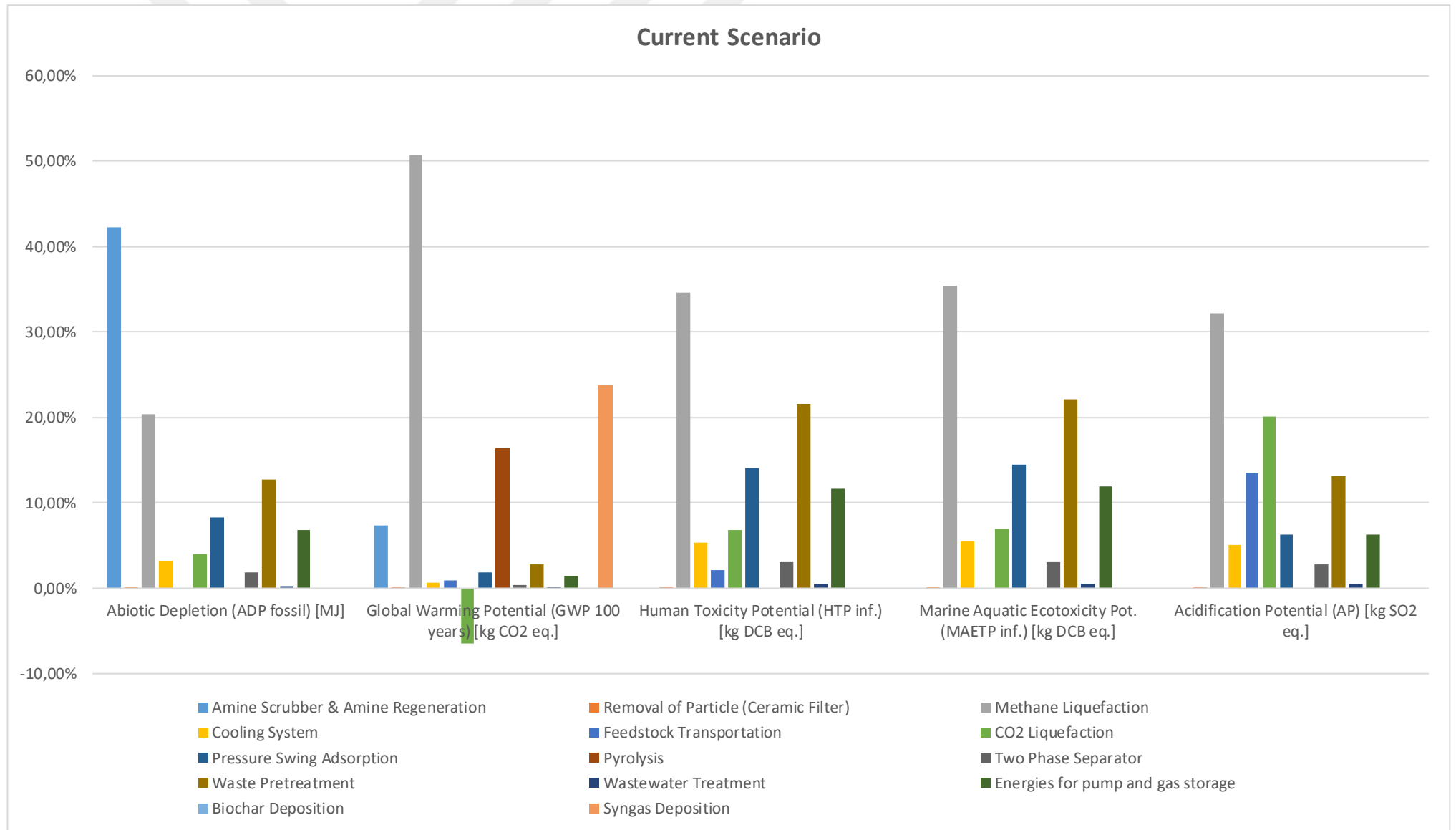


Figure 4.6. The characterization of current scenario.

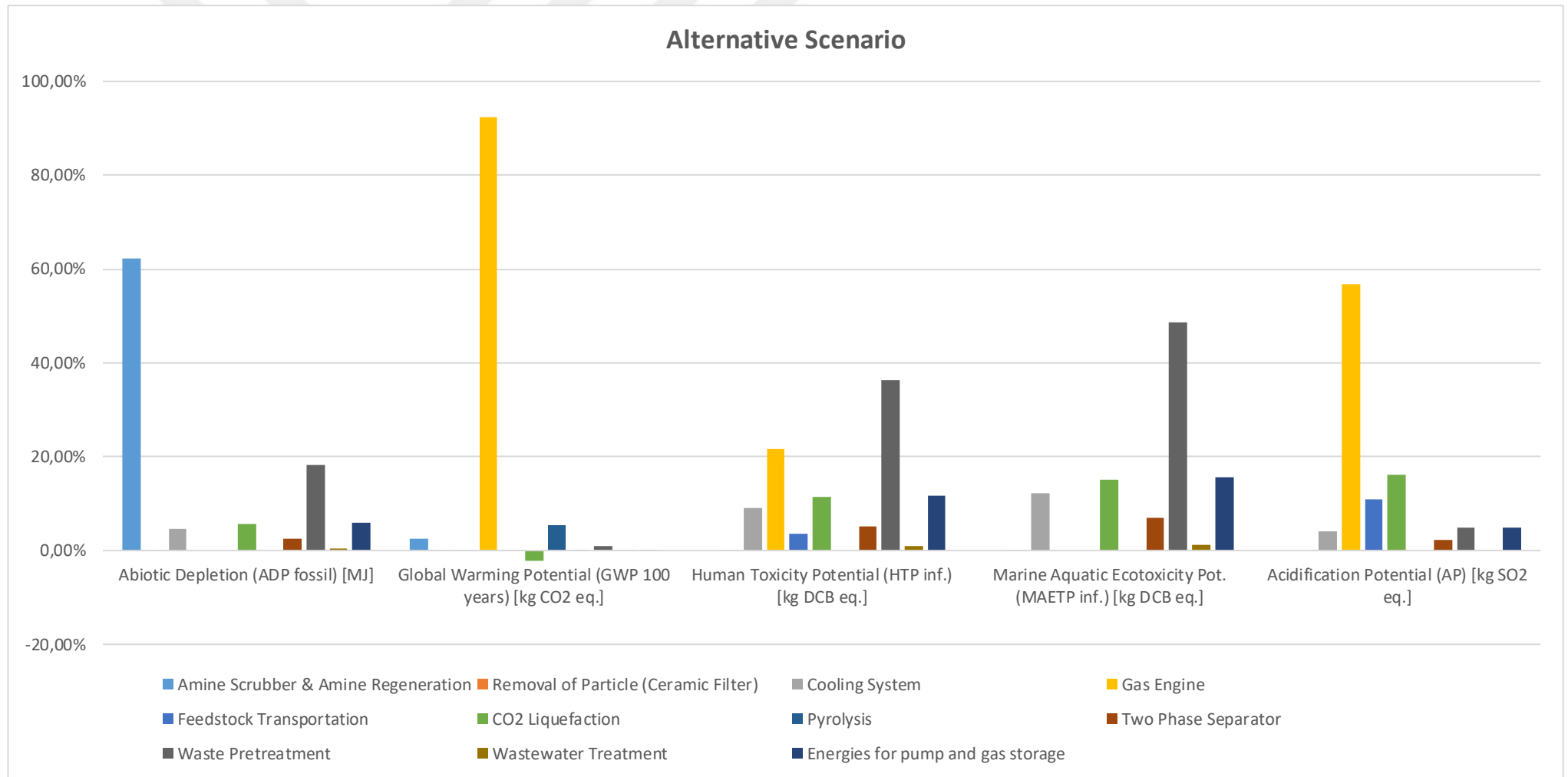


Figure 4.7. The characterization of alternative scenario.

4.1.3. Normalization

In the Life Cycle Assessment (LCA) methodology, normalization is a critical step that scales the environmental impacts of a system under investigation to a common reference, making comparisons across different environmental impact categories feasible and meaningful. This scaling is accomplished by dividing the impact results by a reference value, often derived from global or regional averages. The choice of the normalization reference value is crucial, as it defines the context in which the system's impact is interpreted. Commonly used references include the total environmental burden for a given area (e.g., country-level or global average impact per capita) or benchmark values established by authoritative databases such as the U.S. EPA or the Ecoinvent database (Bjørn et al., 2020). These references enable the conversion of raw impact data into relative values that can be compared across different categories (e.g., climate change potential, acidification, eutrophication, etc.) (Muhl et al., 2021).

In this study, the normalization procedure was carried out using the CML2001 method (version January 2016), a widely recognized framework for LCA impact assessment (Guinée et al., 2010). The normalization reference used in this study was derived from global environmental data, specifically from the U.S. Environmental Protection Agency's (EPA) national impact values, which provide a standardized way to compare the environmental loads across different regions and sectors. These reference values represent typical per capita burdens or regional environmental impacts, which are essential for ensuring the contextual relevance of the normalization results. For instance, the global warming potential (GWP) reference values are derived from global average CO₂ equivalent emissions, allowing for a direct comparison of the system's GWP against the global average impact (Bjørn et al., 2020).

Figure 4.8 presents the normalized impact results for both the current and alternative scenarios, showcasing the distinct environmental burdens associated with each.

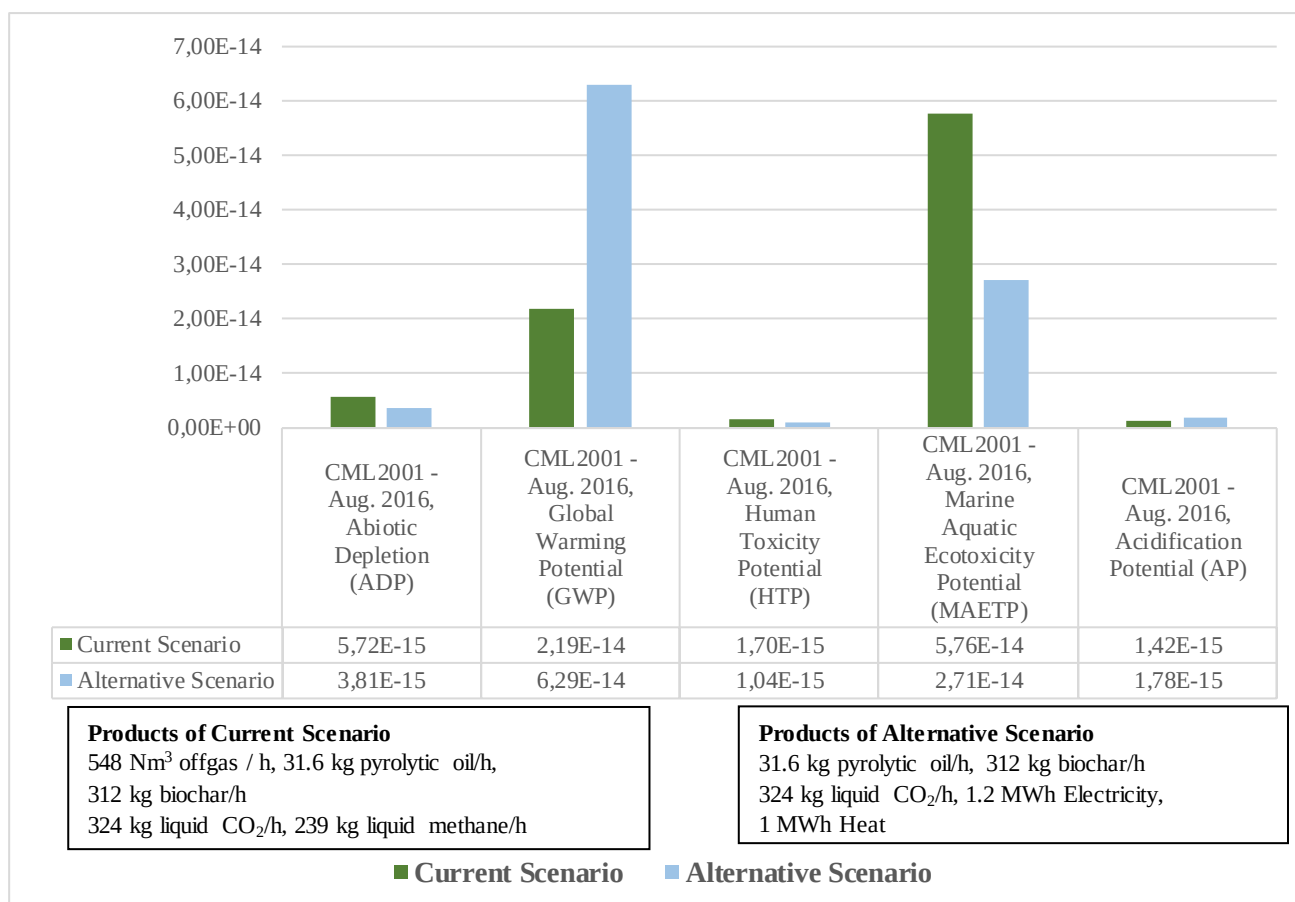


Figure 4.8. Normalization results of scenarios.

Upon a detailed examination of the normalized results, the Marine Aquatic Ecotoxicity Potential (MAETP) appears as the most prominent impact in the current scenario. This outcome is primarily attributed to the substantial electricity consumption in the system. The electricity generation in this scenario relies heavily on fossil fuels (coal, natural gas), which are associated with significant environmental burdens, such as acidification, photochemical ozone formation, and global warming. Fossil fuel combustion for electricity generation emits not only CO₂ but also sulfur oxides (SO_x) and nitrogen oxides (NO_x), which contribute to acidification and smog formation, elevating the MAETP impact in this scenario. The normalization procedure reveals the significant contribution of these emissions, which disproportionately affect environmental quality when compared to other impacts, such as land use or water consumption.

In contrast, the alternative scenario's normalization results indicate that the Global Warming Potential (GWP) of the gas engine used for electricity and heat generation is the most significant impact factor. This shift suggests that while the alternative scenario reduces the overall number of processes involved (e.g., it eliminates some electricity generation processes), the remaining processes, specifically the gas engine, are more carbon-intensive than the fossil-fuel based electricity

grid used in the current scenario. Gas engines, although more efficient in energy conversion compared to traditional fossil fuel plants, still emit considerable amounts of CO₂ and other greenhouse gases, contributing heavily to the GWP (Bjørn et al., 2020). This observation highlights the importance of considering not only the number of processes involved but also the specific technologies used and their respective efficiencies and emissions profiles.

In conclusion, the normalization results underscore critical differences between the two scenarios. The higher MAETP value in the current scenario is predominantly due to electricity consumption from fossil fuels, which leads to higher emissions across multiple environmental categories. On the other hand, the alternative scenario's higher GWP value points to the dominance of the gas engine in terms of greenhouse gas emissions, despite a reduction in the total number of processes. This analysis demonstrates that normalization is not just a methodological step, but a vital tool for understanding the relative significance of different environmental impacts and providing a more scientific and contextually relevant comparison of various systems and technologies.

5. CONCLUSION

This study looks at the different types of impacts in different situations by using a gate-to-gate approach for an LCA and making useful products from label waste that is made up of plastic and paper. In addition, this study provides a comparative analysis of the pyrolysis and incineration methods which is baseline method, highlighting the environmental advantages and disadvantages of each. By aligning with existing literature, the study offers decision-makers valuable insights into the potential benefits of alternative waste treatment methods, supporting informed choices toward environmentally sustainable solutions.

This study creates two scenarios using different processes for label waste, resulting in different products. In both scenarios, 31.6 kg/h of pyrolysis oil, 312 kg/h of biochar, and 324 kg/h of liquid CO₂ are obtained. In contrast, in the current scenario, unlike the alternative scenario, 798 nm³/h of syngas and 239 kg of LNG/h of green methane are produced. In the current scenario, the high-purity syngas purified from CO₂ in the amine scrubber units enter the PSA unit, separating it into two gases: CO & H₂, and CO & CH₄. While 20% of the syngas containing CO and H₂ meet the energy needs of the pyrolysis system, 80% fulfill the energy requirements of other industries. The separated CO₂ and CH₄ were purified using a membrane unit, resulting in the production of 239 kg/h of green LNG in the methane liquefaction unit. As a result, the system has gained the capacity to produce its energy, and green methane, which is a high-value-added product, has been obtained. In an alternative scenario, the gas exiting the amine scrubber unit is burned directly in the gas engine to produce 1.2 MWh of green electricity and 1 MWh heat. However, in this case, the energy needs of the pyrolysis system had to be met from external sources. This situation is reducing the energy efficiency of the system and limiting the possibility of obtaining additional products.

The goal is to evaluate and compare the environmental impacts of various processes for waste management and energy-producing facilities while obtaining different products. The CML2001 method (version released in January 2016) was used as part of an environmental assessment framework to look at four main impact areas: abiotic depletion, global warming potential, human toxicity potential, and marine aquatic ecotoxicity potential. Additionally, this study incorporated an optional stage within the framework, specifically focusing on the relative significance of these impacts on a global scale, thanks to the normalization step. In each scenario, the processes were segmented into distinct stages. The subsequent evaluation included a comparative analysis of the two scenarios as well as an intra-scenario examination of the various stages.

The current scenario characterization results indicate that the GWP impact in the alternative scenario is approximately two and a half higher than it is in the current scenario. The main reason is the high CO₂ emissions from the gas engine used to generate electricity in the alternative scenario (accounting for 92% of the total GWP). In contrast, the dominant contributor to GWP within the current scenario is the consumption of LNG used as a result of methane liquefaction and the use of syngas used instead of natural gas in different industries.

The study proposes a CO₂ capture and utilization strategy where, following separation from syngas in the amine scrubber, the CO₂ is liquefied and injected directly into greenhouses. This approach demonstrably reduces the GWP impact by 22% in the current scenario and 2% in the alternative scenario. Furthermore, the analysis reveals a two-fold more significant impact on the MAETP in the current scenario than the alternative. This disparity is primarily attributed to the heightened sensitivity of MAETP to electricity consumption. As electricity demand increases, so does the value in this category. The underlying reason lies in the adverse effects of fossil fuel combustion on marine life. Burning fossil fuels to generate electricity releases greenhouse gases that acidify the marine environment, alter water temperatures, and cause fluctuations in water levels. The current scenario consumes significant electricity in processes such as methane liquefaction, waste pretreatment, PSA units, pumps, gas storage, and other stages. In the alternative scenario, waste pretreatment has the highest impact on MAETP, accounting for 49% of the total impact. According to MAETP's findings, electricity is the primary factor influencing HTP values in the two scenarios examined in this study.

Consequently, the current scenario exhibits a higher HTP value due to increased electricity consumption. However, the impact on HTP is less pronounced than in MAETP because electricity generation does not exert such detrimental effects on human health. By replacing the external natural gas supply with internally produced syngas to meet the energy needs of the pyrolysis system, the environmental impact, as measured by the rate of abiotic depletion, was reduced by 55-63% in current and alternative scenarios. In the both scenario, the primary driver of ADP is the natural gas used in the amine scrubber and regeneration units for CO₂ separation from the syngas.

The normalization results showed that the MAETP impact category had the highest normalization score in the current scenario. This observation can be attributed to the significantly higher electricity consumption associated with the methane liquefaction unit employed in the alternative scenario. The GWP impact category received the highest normalization score in the alternative scenario due to the high greenhouse gas emission rate associated with using gas engines to generate electricity and heat.

Despite having fewer processes, the total normalization score for the alternative scenario was higher than for the current scenario. To get a better look at the difference in how well the environment is doing, the pyrolysis resource in the other scenario can be treated using different methods instead of letting the CO₂ from the system's syngas and gas engine escape into the air. This can then be compared to the first scenario. In addition, to make the study more comprehensive, LCA studies can be developed and compared with different scenarios using different feedstocks, such as glass and biomass waste.

Traditional method have a GWP impact approximately 2.5 times higher than that of current scenario. Additionally, the incineration process yields only 1.59 kWh/kg of label waste electricity, positioning it as the least favorable option within the waste hierarchy and providing limited contributions to environmental sustainability. In contrast, the establishment of a pyrolysis facility represents an alternative that aligns with circular economy principles and supports the United Nations Sustainable Development Goals (SDGs). This pyrolysis scenario not only results in lower GWP impacts but also enables the production of high-value products, such as pyrolytic oil and biochar. Consequently, waste can be transformed into valuable products that offer greater environmental and economic benefits beyond mere energy recovery. When assessed from these perspectives, the current scenario emerges as a more effective and long-term solution in line with sustainability objectives.

This study explored the potential of recycling and converting label waste into energy through pyrolysis. The findings presented here align with several SDGs established by the United Nations and inspire hope for a more sustainable future. By diverting label wastes from landfills and transforming them into usable products like syngas, green LNG, and biochar, this approach contributes to SDG 7 (Affordable and Clean Energy) by reducing reliance on fossil fuels and promoting renewable energy sources. It also supports SDG 9 (Industry, Innovation, and Infrastructure) by fostering the development of new waste management technologies and creating opportunities for small and medium-sized enterprises (SMEs). Furthermore, improving city waste management infrastructure promotes SDG 11 (Sustainable Cities and Communities). In 2030, achieving targets like 7.1 (universal access to affordable energy) and 7.2 (increased share of renewables in the global energy mix) will be critical. Pyrolysis offers a solution that aligns with these targets by providing a clean and sustainable energy source. By 2050, large-scale adoption of pyrolysis could significantly contribute to SDG 12 (Responsible Consumption and Production) by minimizing waste generation and promoting resource efficiency. Additionally, widespread implementation can support SDG 13 (Climate Action) by reducing greenhouse gas emissions through fossil fuel displacement and CO₂ capture. In conclusion, exploring chemical recovery like pyrolysis presents a promising approach for

achieving a more sustainable future, as evidenced by its alignment with multiple SDGs and their associated 2030 and 2050 targets.



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APPENDIX A: IMPACT ASSESSMENT

Impact assessments are typically classified as pertaining to either potential or actual impacts. Life cycle assessment (LCA) exclusively concentrates on the maximum potential impact, known as the prospective effect. The principal aim of life cycle impact assessment (LCIA) is to assess and quantify the environmental impacts and repercussions linked to different phases of a product's or process's life cycle, encompassing raw material extraction, manufacture, utilization, and end-of-life disposal. Through the examination of these stages and their associated environmental implications, LCIA discerns problematic areas and potential for enhancement, thereby promoting environmentally responsible decision-making.

This phase of LCA evaluates potential consequences on human health and the environment, encompassing those resulting from energy, water, and material use, along with environmental emissions recorded during the inventory analysis. LCIA assesses the scale and importance of these potential environmental impacts (ISO 14040, 2006). In contrast to other evaluation methodologies like risk assessment, environmental performance assessment, or environmental effect assessment, Life Cycle Impact Assessment (LCIA) adopts a comparison approach focused on a functional unit. Although LCIA may employ data from these methodologies, its principal aim is not to quantify particular real-world consequences but to comprehend a system's potential repercussions.

LCIA process comprises both mandatory and optional elements, which include seven essential steps: impact category selection, categorization, characterization, normalization, grouping, weighting, and data quality analysis. The ISO standards for Life Cycle Assessment (ISO 14040 and ISO 14044) stipulate that the initial three processes—category selection, categorization, and characterization—are obligatory, whereas the subsequent steps are discretionary. A well-articulated purpose and scope are crucial for conforming to the requisite criteria. The study's objective frequently determines the use of LCIA indicator approaches. For instance, if the goal is to evaluate land use or fossil fuel consumption, particular indicators must be employed to substantiate these results. Consequently, the selected impact assessment methodologies must be generally acknowledged and tightly matched with the study's specified objectives and parameters.

According to ISO 14040 and ISO 14044, the second obligatory step, classification, entails categorizing emissions into pertinent midpoint indicator groups. Each emission may belong to one or several categories, and this classification underpins subsequent study. Table A.1. delineates the

classification of emissions based on midpoint indicators and their corresponding scales. Characterization, the next phase, quantifies the contribution of each inventory emission to its corresponding effect category. The computation of midpoint indicator findings involves summing the contributions of the characterization criteria for each category. Contemporary LCA software automates the procedures of classification and characterization (Tolon, 2024).

To provide data in a consistent and comparable manner, the optional process of normalization splits midpoint category values by a reference value, such as per capita, global, regional, or national benchmarks. Grouping, an optional procedure, entails the categorization of impact category indicators into clusters according to criteria such as geographic relevance (e.g., local, regional, or global) or importance levels (e.g., low, medium, or high). Defining these classifications is particularly crucial for creating explicit study objectives.

The weighting process changes the values of midpoint or endpoint indicators by using numbers to show how important different effect categories are. Ultimately, LCIA elements, including effect categories and regionalized impact evaluations, necessitate additional clarification, especially in the context of bioenergy systems (Vallero, 2014).

Table A.1. The midpoint indicator category of emissions and scale (Tolon, 2024).

Impact Category	Scale	Examples of LCI data
Acidification Potential	Regional, Local	Sulfur oxides (SO _x), nitrogen oxides (NO _x), hydrochloric acid (HCl), hydrofluoric acid (HF), ammonia (NH ₄)
Marina Aquatic Ecotoxicity Potential	Local	Toxic chemicals with a reported lethal concentration to fish
Global Warming Potential	Global	Carbon dioxide (CO ₂), nitrous oxide (N ₂ O), methane (CH ₄), chlorofluorocarbons (CFC _s), hydrochlorofluorocarbons (HCFC _s), methylbromide (CH ₃ Br)
Human Toxicity Potential	Global, Regional, Local	Total releases to air, water, and soil
Abiotic Depletion	Global, Regional, Local	Quantity of minerals used, quantity of fossil fuels used

APPENDIX B: NORMALIZATION

Normalization, a discretionary step within LCA, involves scaling potential environmental impacts (midpoint or endpoint) against a global. This process aims to unify diverse impact units into a common scale. By referencing a specific benchmark, normalization highlights the relative significance of each impact category. Normalization factors (NFs) are applied to both midpoint and endpoint indicators. Derived from the aggregate impacts of a reference system, such as a geographic region, NFs provide a standardized metric for comparing environmental burdens (Lautier et al., 2010).

$$N_i = \frac{S_i}{NF_i} \quad (B.1)$$

Where:

i stands for the impact category,

N stands for the normalized result,

S stands for the impact score of a product,

NF stands for the normalization factor.

Normalization factors (NFs) must be determined based on the specific normalization goal and adhere to the International Organization for Standardization (ISO) guidelines for Life Cycle Assessment (LCA). The ISO framework allows for various normalization approaches. NFs are derived from emissions and resource consumption data at both national and individual levels, expressed annually per person.

$$NF_i(national) = \sum CF_s * E_s \quad (B.2)$$

$$NF_i(per\ person) = \frac{\sum CF_s * E_s}{P} \quad (B.3)$$

Where:

$NF_i(national)$ stands for the normalization factor (/year) for the impact category i,

$NF_i(per\ person)$ stands for the normalization factor (/year·person) for the impact category i,

CF stands for the characterization factor (Impact/kg) of a given substance “s”,

E stands for the emissions of “s” in a country (kg/yr) and

P stands for the population of a country (Persons).

The proposed methodology calculates a country normalization factors by considering the annual emissions and resource extraction within a country's' borders for the baseline year. Characterization factors, along with relevant substance data for each impact category, are applied to compute the NFs. Figure B.1. illustrates the procedural steps involved in developing the NF dataset for Life Cycle Assessment (LCA) in a country. To highlight the key distinctions between our findings and international NFs, a comparative analysis is conducted (Chen et al., 2024).

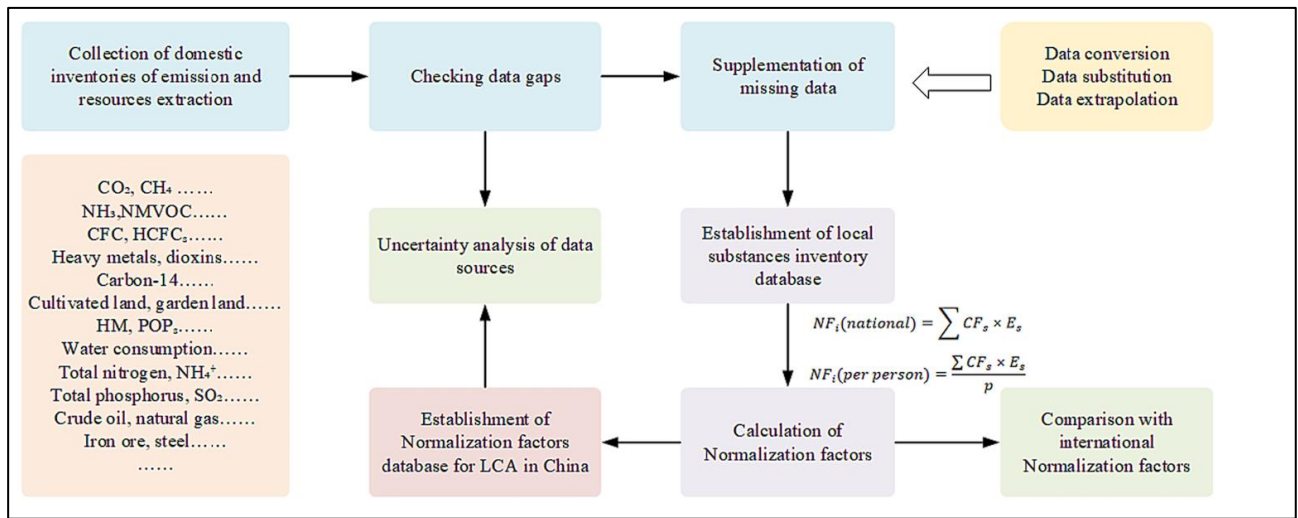


Figure B.1. Flowchart of NFs database construction in a country (Chen et al., 2024).

Climate change assessments within LCA methodologies commonly employ Global Warming Potentials (GWPs) as midpoint characterization factors. This practice is rooted in their foundation on cutting-edge, peer-reviewed research and their relatively low associated uncertainty. GWPs quantify the incremental radiative forcing over a specified timeframe caused by a unit mass of a greenhouse gas (GHG) relative to that of a unit mass of CO₂ (Stocker et al., 2014).

To establish a consistent NF database compatible with the characterization factors, a unit conversion process was necessary. This involved dividing the emissions data by the corresponding carbon dioxide equivalent coefficients, resulting in mass units.

$$M = \frac{MCO_2}{Q} \quad (B.4)$$

Where:

MCO₂ stands for the equivalent emissions of CO₂, CH₄, N₂O and SF extracted from the United Nations Convention on Climate change (kg),

Q stands for the carbon dioxide equivalent coefficient of the greenhouse gas,

M represents the mass of the converted gas (kg).

When deriving normalization factors and computing characterization factors, impact categories that significantly influence regional environmental characteristics, such as eutrophication, acidification, and toxicity, should use data gathered by each country that reflects regional boundaries to replace normalization values with greater accuracy. Table B.1. presents the impact category of normalization and weighting variables produced using the CML 2001 technique (Jang et al., 2022).

Table B.1. Normalization factors of impact categories (Jang et al., 2022).

Impact Category	Normalization Factor		Weighting Factor
	Value	Unit	Value
<i>Abiotic Depletion</i>	2,49 x 10 ⁴	g/person-year	2,31 x 10 ⁻¹
<i>Global Warming Potential</i>	5,53 x 10 ⁶	gCO ₂ -eq/person-year	2,88 x 10 ⁻¹
<i>Ozone Depletion Potential</i>	4,07 x 10	gCFC _{-eq} /person-year	2,92 x 10 ⁻¹
<i>Photochemical Ozone Creation Potential</i>	1,03 x 10 ⁴	gC ₂ H ₄ -eq/person-year	6,50 x 10 ⁻²
<i>Acidification Potential</i>	3,98 x 10 ⁴	gSO ₂ -eq/person-year	3,60 x 10 ⁻²
<i>Eutrophication Potential</i>	1,31 x 10 ⁴	g PO ₄ ³⁻ -eq/person-year	3,80 x 10 ⁻²
<i>Effluent Treatment Plant</i>	1,63 x 10 ³	gDCB _{-eq} /person-year	2,16 x 10 ⁻¹
<i>Human Toxicity Potential</i>	1,48 x 10 ⁶	gDCB _{-eq} /person-year	1,05 x 10 ⁻¹

To develop a damage-oriented (endpoint) approach, the LCA necessitated weighting. Three perspectives are available: individualist, hierarchist, and egalitarian. Integrating the endpoint impact categories of harm to human health, ecosystems, and resources establishes three endpoint (damage) categories. A summary of the endpoint approach at the endpoint level and impact assessment categories is presented by integrating these three categories through an indicator measured in points. A summary of the endpoint technique concerning the effect assessment categories and endpoint level is presented in Table B.2. (Rosenbaum et al., 2018).

Table B.2. Endpoint method impact assessment categories (Rosenbaum et al., 2018).

Impact Category	Damage Category		
	Human Health	Ecosystem	Resources
<i>Agricultural Land Occupation</i>		+	
<i>Climate Change – Ecosystem</i>		+	
<i>Climate Change – Human Health</i>	+		
<i>Fossil Depletion</i>			+
<i>Fresh Water Ecotoxicity</i>		+	
<i>Fresh Water Eutrophication</i>		+	
<i>Human Toxicity</i>	+		
<i>Ionizing Radiation</i>	+		
<i>Marine Ecotoxicity</i>		+	
<i>Metal Depletion</i>			+
<i>Natural Land Transformation</i>		+	
<i>Ozone Depletion</i>	+		
<i>Particulate Matter Formation</i>	+		
<i>Photochemical Oxidation Formation</i>	+		
<i>Terrestrial Acidification</i>		+	
<i>Terrestrial Ecotoxicity</i>		+	
<i>Urban Land Occupation</i>		+	

Figure B.2. illustrates the connection between the environmental mechanisms and the midpoints.

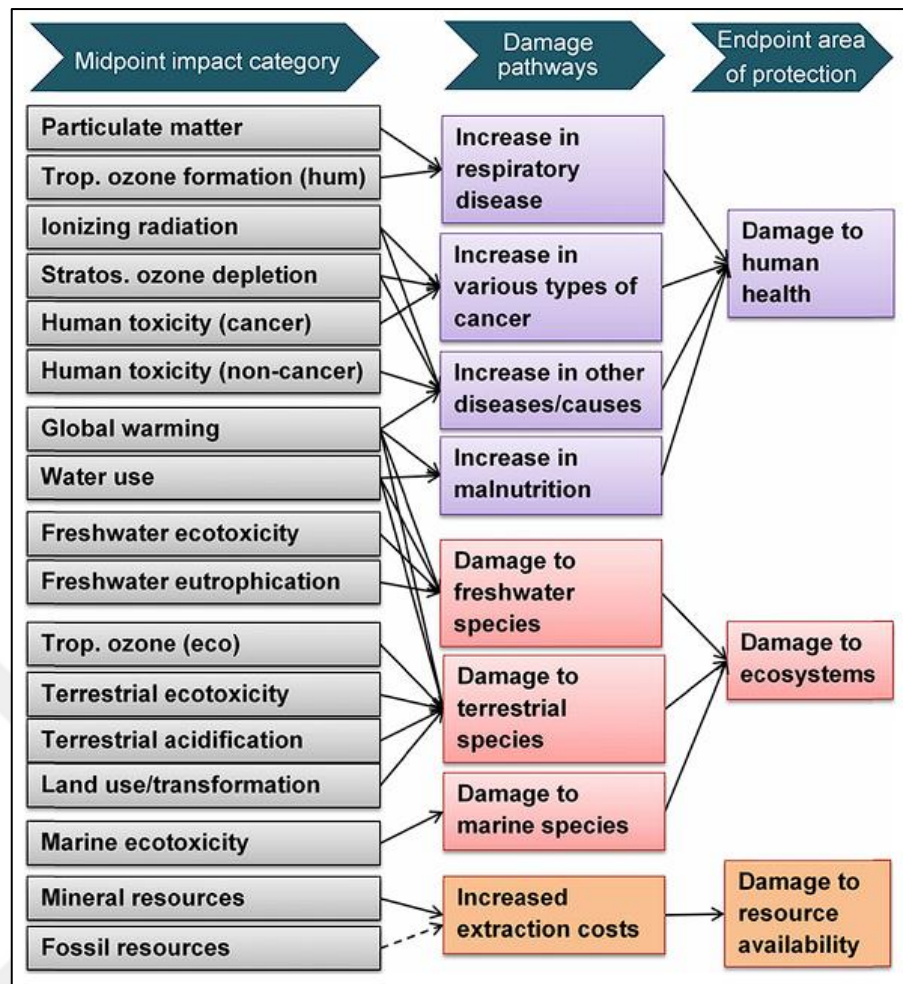


Figure B.2. The connection between midpoint impact categories and endpoints (Huijbregts et al., 2017).

APPENDIX C: CALCULATION METHOD FOR IMPACT CATEGORIES

A calculation method for the selected impact categories has been developed. This method combines characterization factors that determine the environmental impact, normalization factors that express the equivalency of different substances, and emission inventories. As a result, the contribution of different substances to a specific environmental impact can be quantified (Guinée, 2002).

Global Warming Potential (GWP) is expressed in terms of carbon dioxide equivalents. This means that a gas's GWP is a ratio indicating how much warming a given quantity of the gas causes compared to the same amount of carbon dioxide (Guinée, 2002).

$$\text{Global Warming Potential} = \sum_i GWP_{a,i} \times m_i \quad (C.1)$$

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.

In the assessment of climate change impacts, the global warming potential (GWP) is an important indicator and expresses the effects of different greenhouse gases in terms of carbon dioxide equivalent (CO₂ eq.). In this context, five different GWP indicators are calculated: GWP-fossil, which represents the impact of emissions from the combustion of fossil fuels; GWP-biogenic, which represents the impact of biogenic emissions; GWP-land use and land use change, which represents the impact of emissions from land use and land use change. GWP-total is the sum of these three indicators, while GWP-GHG is calculated under the assumption that the characterization factor for biogenic CO₂ is zero. These calculations are carried out over a 100-year time period (GWP100). As emphasized in the IPCC report, gases such as methane (CH₄) and nitrous oxide (N₂O) have much higher GWP values compared to carbon dioxide, with the value for methane determined as 25 kg CO₂ equivalent and for nitrous oxide as 298 kg CO₂ equivalent. Such calculations play a critical role in analyzing the potential impacts of greenhouse gases on global warming and in developing climate change policies.

Table C.1. Global warming potential values relative to CO₂ (IPCC, 2006).

Common Chemical Name or Industrial Designation Major Greenhouse Gases	Chemical Formula	GWP Values for 100 Year Time Horizon Fourth Assessment Report (AR4)
<i>Carbon Dioxide</i>	CO ₂	1
<i>Methane - non-fossil</i>	CH ₄	25
<i>Methane - fossil</i>	CH ₄	N/A
<i>Nitrous Oxide</i>	N ₂ O	298
<i>Nitrogen Trifluoride</i>	NF ₃	17200
<i>Sulfur Hexafluoride</i>	SF ₆	22800

According to Jensen et al. (2019) study, calculation is conducted by juxtaposing a business-as-usual reference scenario with a 2°C target scenario for the globe as seen in Figure C.1. The assessment suggests that the electricity sector, accounting for 39% of the total mitigation effort, may primarily accomplish the necessary greenhouse gas emissions reduction by 2030, followed by the "other energy" sectors at 19%, industry at 18%, agriculture at 10%, buildings at 6%, transport at 4%, and waste at 4%. These figures omit emissions and sinks from the "Land Use, Land Use Change, and Forestry" (LULUCF) sector. Specifically, global greenhouse gas emissions from the economy need to achieve the 2 °C objective. This calculation is conducted by juxtaposing a business-as-usual reference scenario with a 2°C target scenario for the globe The assessment suggests that the electricity sector, accounting for 39% of the total mitigation effort, may primarily achieve the necessary reduction of GHG emissions by 2030, followed by the "other energy" sectors at 19%, industry at 18%, agriculture at 10%, buildings at 6%, transport at 4%, and waste at 4%.

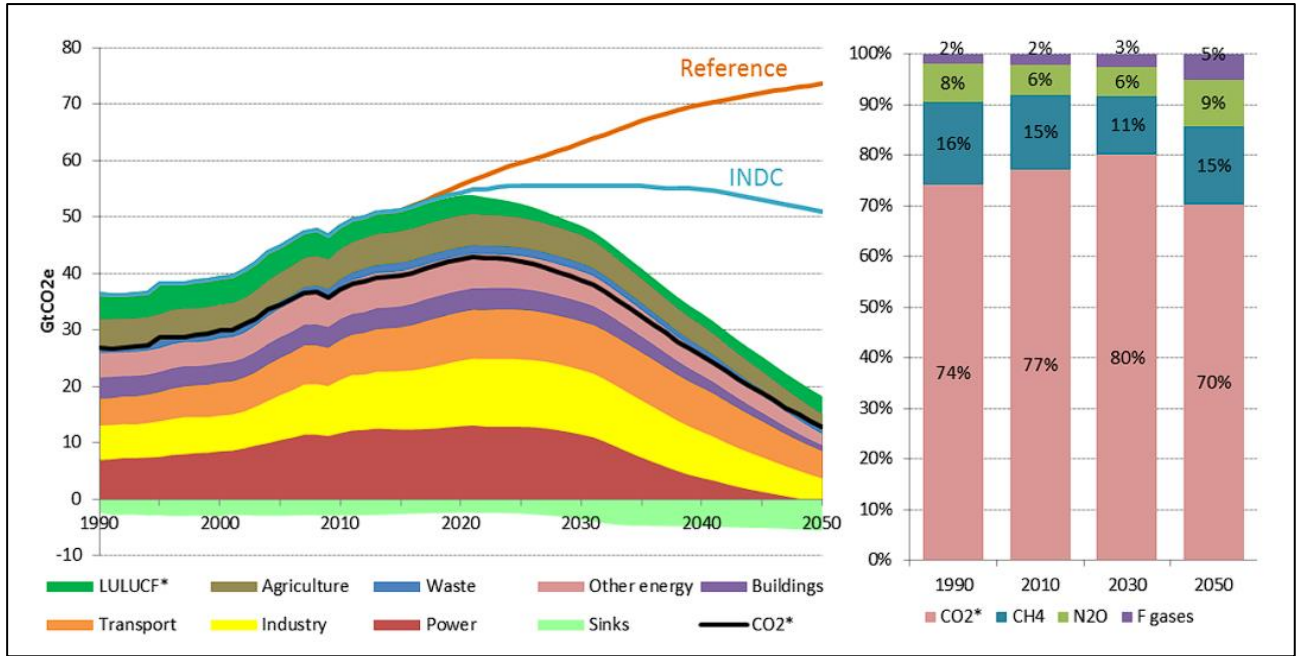


Figure C.1. The greenhouse gas emissions reduction by years (Jensen et al., 2019).

Acidification potential (AP) refers to a substance's or process's capacity to increase the acidity of a medium. This is a crucial parameter, particularly in environmental issues such as air and water pollution. It is often quantified by measuring the amount of SO_2 released into the atmosphere (Guinée, 2002).

$$\text{Acidification Potential} = \sum_i AP_i \times m_i \quad (\text{C.2})$$

Where:

AP_i is the Acidification Potential for substance i emitted to air.

m_i (kg) is the emission of substance i to the air.

The primary air pollutants responsible for acidification are nitrous oxides (NO_x), sulfur oxides (predominantly SO_2), and ammonia (NH_3), as they generate acidic compounds in the atmosphere that then precipitate as "acid rain." SO_2 serves as the reference for assessing the acidification potential (or equivalence factor) of each material. The methodology for determining effect factors for acidifying chemicals is grounded in stoichiometric principles and is generally recognized as seen in Table C.2. (Lindley et al., 2019).

Table C.2. Equivalency factors (EF) for acidifying substances (Lindley et al., 2019).

Substance	EF kg SO ₂ /kg
<i>Sulphur dioxide</i>	1
<i>Sulphur trioxide</i>	0.8
<i>Nitrogen dioxide</i>	0.17
<i>Nitrogen oxide</i>	0.7
<i>Nitrogen oxide</i>	1.07
<i>Ammonia</i>	1.88
<i>Hydrogen fluoride</i>	1.6
<i>Hydrogen chloride</i>	0.88

Figure C.2. illustrates the trend in emissions of nitrous oxides (NO_x), sulfur oxides (predominantly SO₂), and ammonia (NH₃) within the EU, along with its targets for 2030.

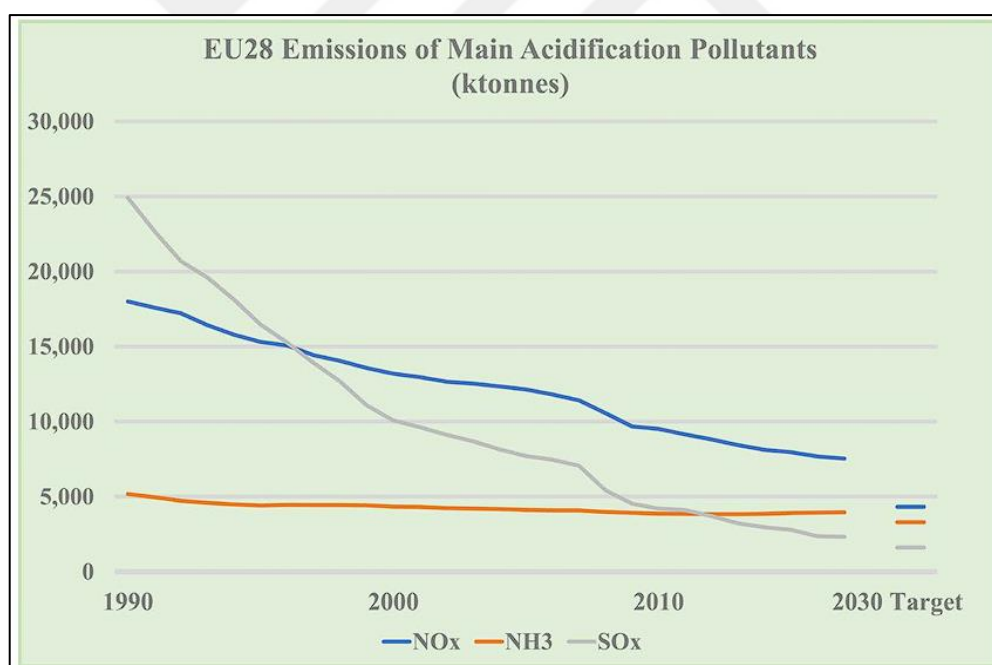


Figure C.2. EU 28 emissions and 2030 targets (Lindley et al., 2019).

Human Toxicity Potential (HTP) and Marine Aquatic Ecotoxicity Potential (MAETP) are concepts that provide information about the overall toxic effects of a group of substances or a process, rather than a specific chemical. 1,4-Dichlorobenzene eq. is commonly used as a reference substance in HTP and MAETP calculations (Guinée, 2002).

$$\text{Marine Aquatic Ecotoxicity Potential} = \sum_i \sum_{ecom} MAETP_{ecom,i} \times m_{ecom,i} \quad (C.3)$$

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.

An examination of contributions indicates that energy usage predominates, accounting for over 90% of the MAETP effect category. Table C.3. shows the analysis of the substances primarily responsible unequivocally indicates that non-ferrous metals are the sole pertinent substances (Hussain et al., 2013).

Table C.3. The responsible substances from marine aquatic ecotoxicity potential (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	Selenium	Water	3,57E+10	27%
2	Nickel	Water	3,47E+10	27%
3	Barium	Water	2,07E+10	16%
4	Vanadium	Air	1,27E+10	10%
5	Vanadium	Water	1,24E+10	9%
6	Copper	Water	5,15E+09	4%
7	Cobalt	Water	2,51E+09	2%
8	Molybdenum	Water	1,61E+09	1%
9	Zinc	Water	1,56E+09	1%
10	Nickel	Air	1,09E+09	1%
11	Selenium	Air	9,79E+08	1%
	Above Substances	-	2,60E+11	99%

$$\text{Human Toxicity Potential} = \sum_i \sum_{ecom} \text{HTP}_{ecom,i} \times m_{ecom,i} \quad (C.4)$$

Where:

$\text{HTP}_{ecom,i}$ is the characterization factor for substance i emitted to emission compartment.

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

According to table C.4., characterized factor of SO_x , NO_x , CO and PM_{10} are shown in 1,4-dichlorobenzene (Li et al., 2012).

Table C.4. The characterization factor of human toxicity potential (Li et al., 2012):

HTP Substances	Characterization Factor(kg 1,4- $\text{C}_6\text{H}_4\text{Cl}_2\text{-eq}$)
SO_x	0.096
NO_x	1.2
CO	0.012
PM_{10}	0.82

Abiotic depletion refers to the exhaustion of finite, non-renewable natural resources (such as minerals, metals, and fossil fuels) on Earth (Guinée, 2002).

$$\text{Abiotic Depletion} = \sum_i \text{Factor}_i \times m_i \quad (C.5)$$

$$\text{Factor}_i = \frac{\text{EX}_i}{\text{molew}_i} \quad (C.6)$$

Where:

Factor_i is the characterization factor for abiotic depletion of resource i based on the exergy content,

$m_i(\text{kg})$ 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 .

The methodology, derived from fundamental research by Guinée et al. (2002), offers a systematic framework for assessing the extraction and utilization of fossil fuels, including coal,

regarding their capacity to deplete abiotic resources. The energy content of fossil fuels is assessed, with hard coal yielding around 27.91 MJ per kilogram and soft coal (lignite) yielding about 13.96 MJ per kilogram. These values are utilized to assess the depletion potential of various fossil fuel kinds, providing a foundation for comprehending the environmental consequences of resource extraction and utilization in industrial operations.

The year 2000 is utilized as the baseline for global resource extraction and utilization, with data for 2010 and projected business-as-usual (BAU) trends until 2030 presented for comparative analysis in Figure C.3. (Bringezu, 2015).

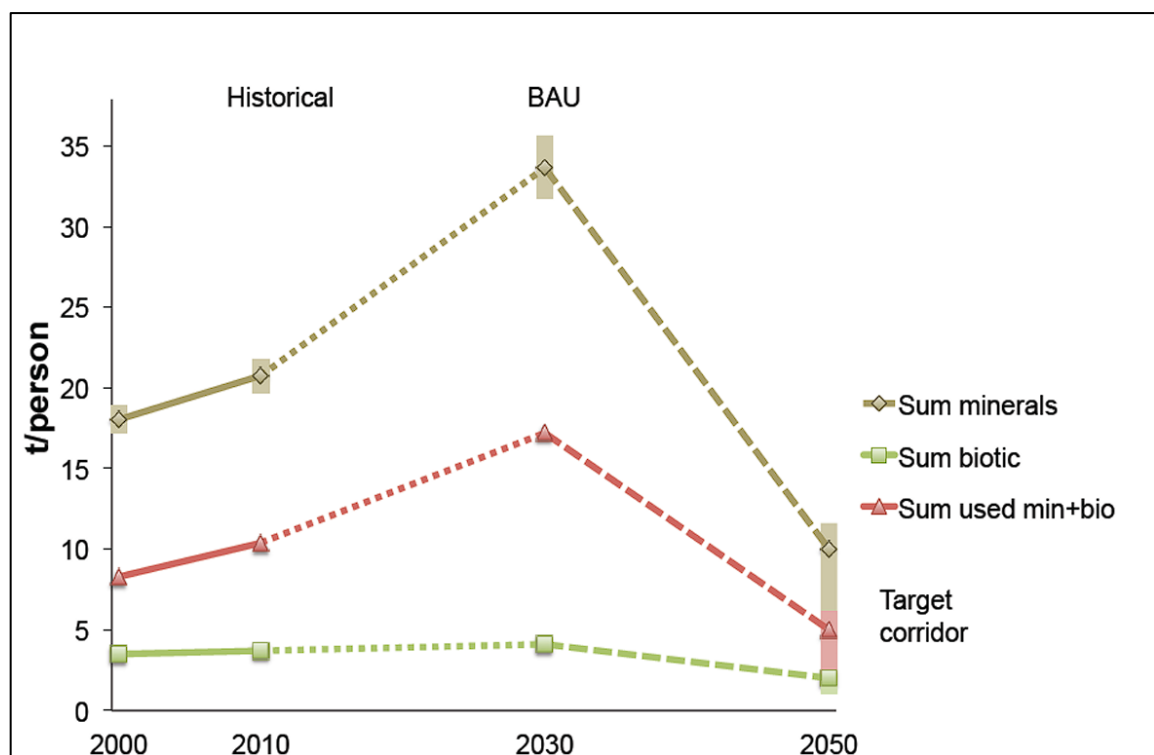


Figure C.3. Summary of worldwide resource flows from 2000, projected business-as-usual trajectory until 2030, and prospective target range until 2050 (Bringezu, 2015).

To assess the primary contributors to various environmental impact categories, Crenna et al. (2019) compared findings. Their proposed global NFs, also based on 2010 data, employ the International Reference Life Cycle Data System (ILCD) (Handbook, 2010) midpoint indicators and the EU Environmental Footprint (EF) set. The results are presented in Figure C.4. : Figure C.7.

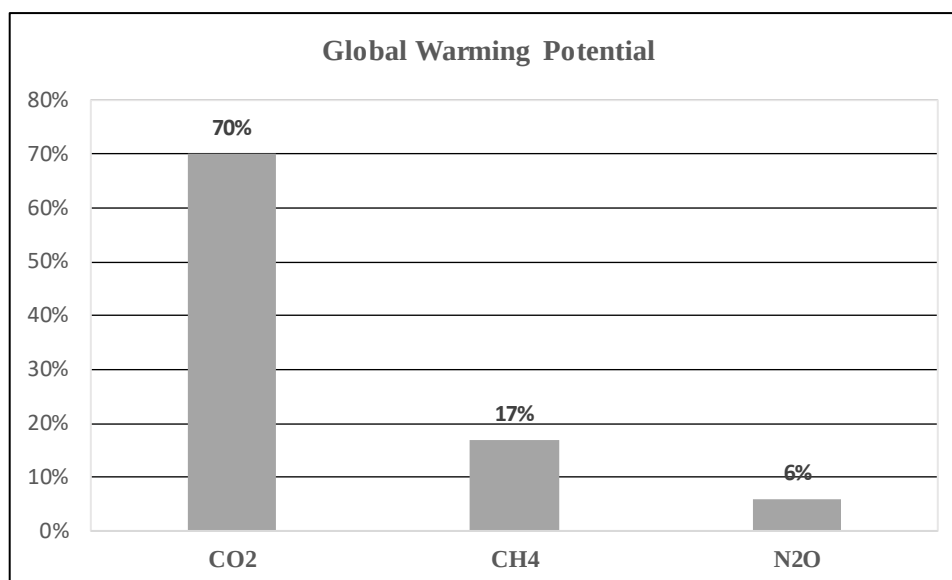


Figure C.4. Characteristic pollutants of global warming potential (Crenna et al., 2019).

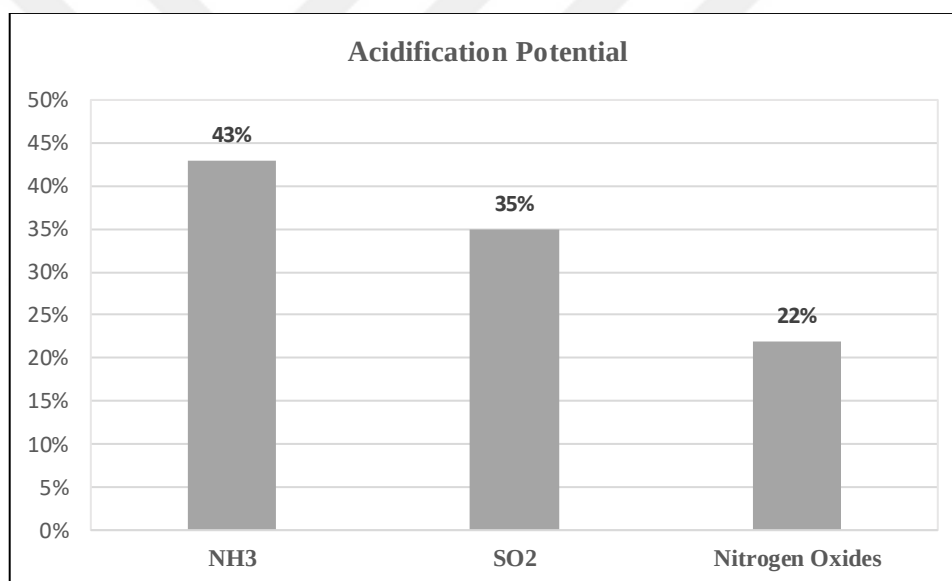


Figure C.5. Characteristic pollutants of acidification potential (Crenna et al., 2019).

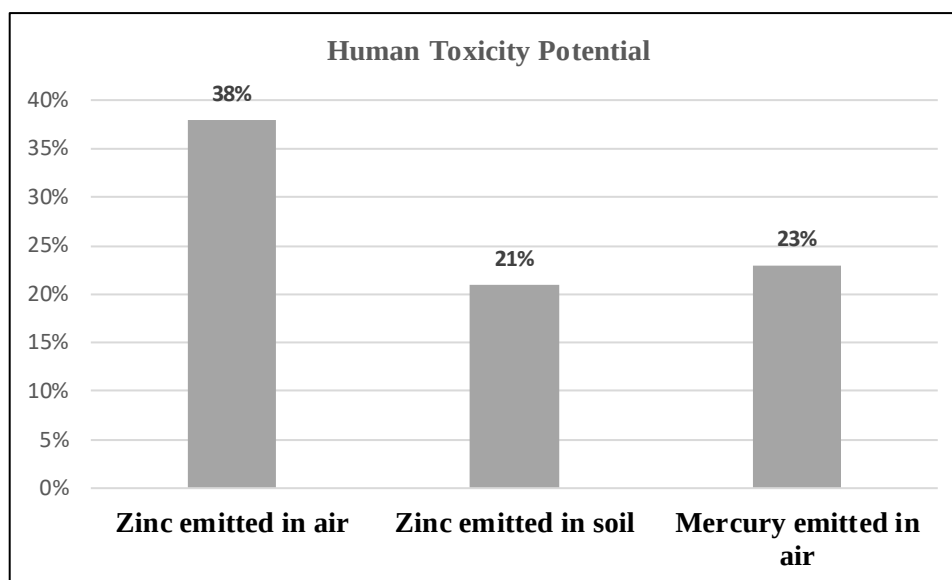


Figure C.6. Characteristic pollutants of human toxicity potential (Crenna et al., 2019).

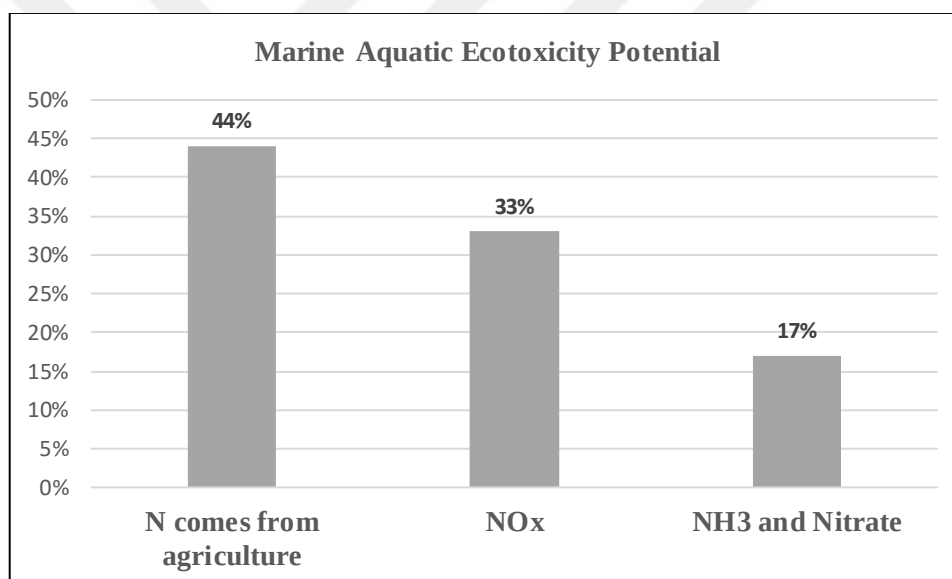


Figure C.7. Characteristic pollutants of marine aquatic ecotoxicity potential (Crenna et al., 2019).

APPENDIX D: CML 2001 METHODOLOGY

Life cycle impact assessment (LCIA) widely uses the CML method. Figure D.1. presents a detailed overview of the CML methodology. Several features distinguish CML from other LCIA methods, as outlined by Bałdowska-Witos et al. (2021):

Midpoint Approach: The CML methodology emphasizes specific environmental impact categories, such as global warming potential (GWP), acidification potential, and eutrophication potential. By adopting a midpoint approach, CML reduces uncertainties in the cause-effect relationships within impact categories. This method enables a more targeted analysis compared to endpoint approaches like ReCiPe. For instance, CML is particularly suitable for studies requiring a focused assessment of greenhouse gas emissions or toxicity effects.

Categorical Impact Areas: CML examines ten distinct impact categories, facilitating detailed and comprehensive analyses of specific environmental issues. This level of categorization allows researchers to gain a deeper understanding of environmental impacts.

Scientific Rigor and Global Relevance: The CML method primarily aims to assess global-scale environmental impacts, unlike regionally tailored methods like TRACI. Its strong scientific foundation, extensive documentation, and regular updates have led to its widespread acceptance. These attributes have contributed to its prevalence in academic research. Moreover, CML aligns with international standards, including ISO 14040 and ISO 14044, enhancing its credibility and applicability.

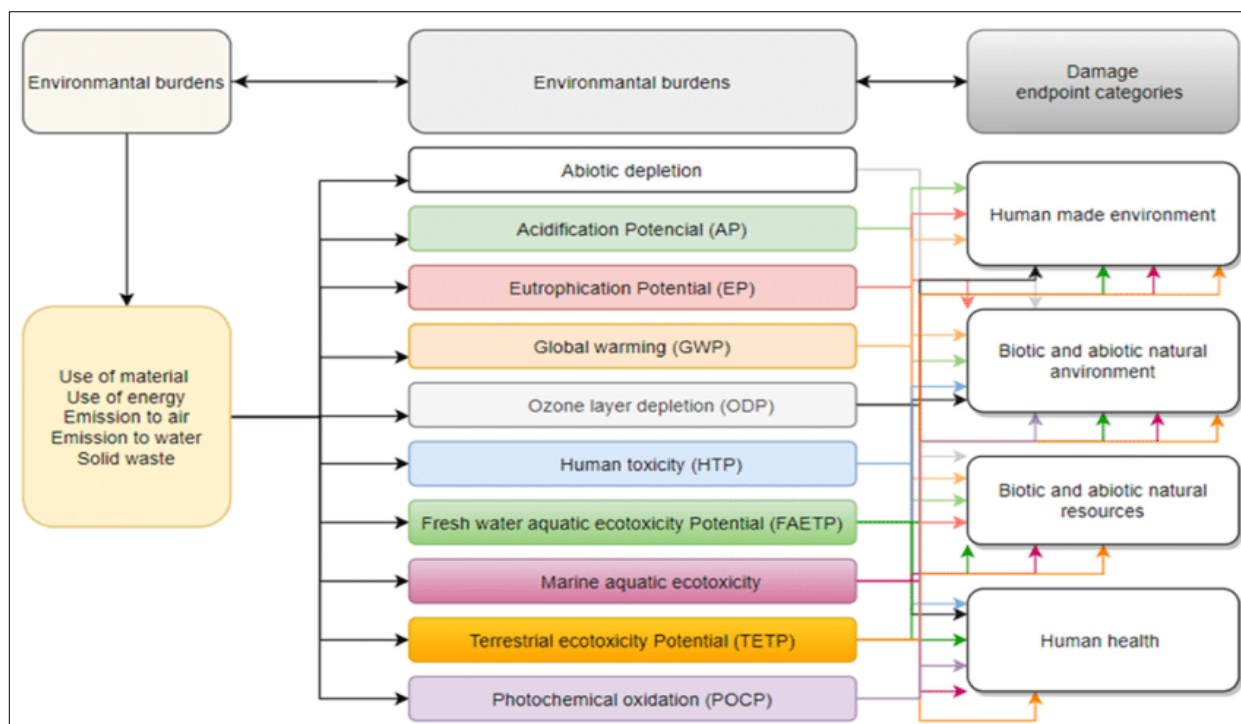


Figure D.1. Comprehensive map for CML methodology (Bałdowska-Witos et al., 2021):

APPENDIX E: ANALYSIS OF PYROLYSIS OF POLYMERS

Pyrolysis involves breaking down the complex polymer chains into smaller molecules, including oligomers and monomers, yielding a diverse range of liquid, gas, and solid char products. The liquid fraction, in particular, holds significant potential as a fuel source, contributing to energy sustainability. The yield and composition of pyrolysis products are influenced by various factors, such as temperature, reaction time, and the presence of catalysts. Catalysts, in particular, can accelerate the bond-breaking process, extending the reaction time or reducing the required temperature, and consequently increasing the gas yield. Therefore, precise control over operating conditions is crucial for maximizing oil production. Additionally, reactor design plays a pivotal role, with factors like heat supply rate, heat transfer mechanism, and residence time significantly impacting product yield and composition (Maqsood et al., 2021).

Three primary reactor configurations exist: slow pyrolysis, fast pyrolysis, and flash pyrolysis. Slow pyrolysis, characterized by low heating rates, long residence times, and low temperatures, is suitable for larger particle sizes (5-50 mm) but incurs higher energy costs due to prolonged reaction times (300-3600 seconds). In contrast, fast and flash pyrolysis offer more efficient alternatives. Fast pyrolysis employs shorter residence times (less than 2 seconds), smaller particle sizes (less than 1 mm), and higher heating rates, commonly utilizing fluidized bed, conical spout bed, and circulating fluidized bed reactors. Flash pyrolysis, an extreme form of fast pyrolysis, operates at even higher temperatures and shorter residence times (less than 1 second), requiring the smallest particle sizes (less than 0.2 mm). Both fluidized and fixed-bed reactors can be employed for flash pyrolysis. Previous research has primarily focused on the pyrolysis of individual plastic types, such as high-density polyethylene (HDPE), low-density polyethylene (LDPE), polypropylene (PP), and polystyrene (PS). HDPE and PP typically yield olefin-rich oil, while PS produces aromatic compounds. However, limited research has explored the pyrolysis of mixed plastic waste streams, which better reflects real-world waste composition. While the oil fraction has garnered significant attention for its potential to produce gasoline and diesel fuels, the energetic value of the gas fraction, which can be utilized as a fuel source to reduce overall energy consumption, deserves further investigation. In Europe, HDPE, LDPE, PP, PS, polyvinyl chloride (PVC), and polyethylene terephthalate (PET) are the most prevalent municipal solid waste plastics, with polyethylene (PE) being particularly abundant due to high consumption rates (Calero et al., 2023).

Figure E.1. presents the outcomes of gas, oil, and char yields derived from the pyrolysis of various plastics. The plastic type significantly influenced the oil yield, resulting in diverse yields for different plastics.

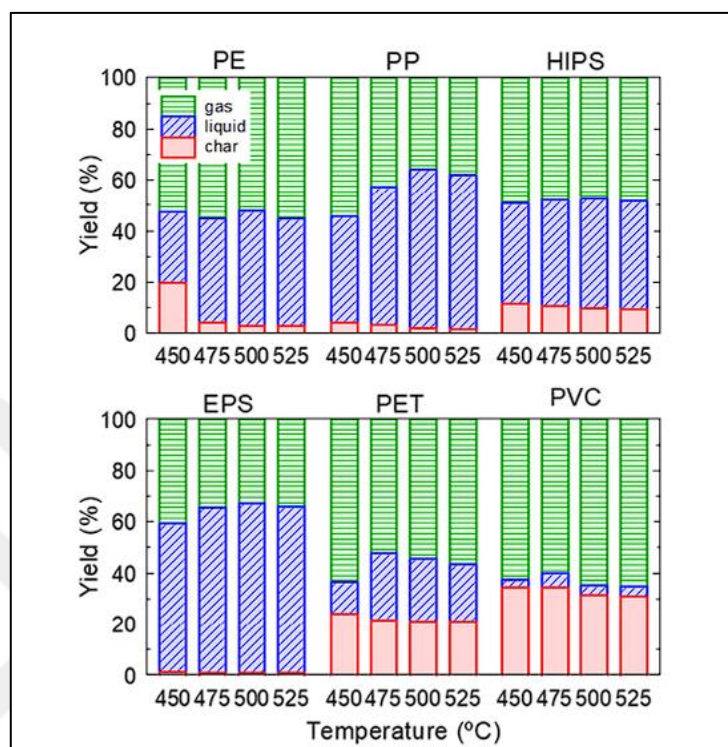


Figure E.1. Product yields from pyrolysis of different polymers (Calero et al., 2023).

Table E.1. presents the elemental analysis and the higher heating value of the oil derived from the pyrolysis of various polymers. The oils derived from PE and EPS exhibit the highest carbon proportions, at 84.3% and 83.2%, respectively. Nonetheless, in relation to hydrogen, PE and PP attained the highest percentages (Calero et al., 2023):

Table E.1. Elemental composition of polymers (Calero et al., 2023).

Material	Elemental Composition (%)						HHV (MJ.kg ⁻¹)
	N	C	H	S	O	Cl	
HIPS	0.32	76.59	8.36	n.d.	14.73	n.d.	35.32
EPS	0.17	83.17	8.72	n.d.	7.94	n.d.	39.28
PE	0.3	84.28	13.79	n.d.	1.63	n.d.	48.06
PP	0.18	84.9	12.95	n.d.	1.97	n.d.	43.28
PVC	0.11	56.88	8.76	n.d.	34.09	0.16	18.45
PET	0.03	62.99	5.68	n.d.	31.3	n.d.	23.9

APPENDIX F: ANALYSIS OF PYROLYSIS OF CELLULOSE

The escalating depletion of traditional fossil fuels and the intensifying environmental pollution have necessitated the exploration of sustainable energy sources. Biomass, a renewable resource with increasing annual production, has been predominantly utilized through direct combustion, leading to significant greenhouse gas emissions. Consequently, the efficient and clean utilization of this abundant waste material has become imperative. Biomass can be processed through various techniques, including pyrolysis, gasification, combustion, hydrothermal liquefaction, and hydrothermal carbonization. Among these methods, pyrolysis, which converts biomass into bio-oil, offers a promising approach for the efficient and clean utilization of biomass. Bio-oil can serve as a potential replacement for fossil fuels or as a source of valuable chemical and medical products. This approach represents a clean and economically viable application of biomass pyrolysis (Chen et al., 2019).

Zhao and his colleagues (2017) observed that the yield and composition of volatile products, including bio-oil and bio-gas, generated from the pyrolysis of cellulose, hemicellulose, and lignin were significantly influenced by pyrolysis conditions and the intrinsic chemical structure of each component. Pyrolysis temperature emerged as a crucial factor in determining the optimal conditions for maximizing bio-oil yield. For cellulose, hemicellulose, and lignin, peak bio-oil yields of 64.70%, 41.44%, and 39.73%, respectively, were achieved at 500 °C, 450 °C, and 600 °C. Cellulose primarily contributed to bio-oil formation, while hemicellulose played a dominant role in bio-gas production. Notably, the bio-gas yield from all three components increased with rising temperature, although the specific gas compositions varied across samples. Cellulose pyrolysis favored CO production due to its higher carbonyl content, hemicellulose pyrolysis yielded more CO₂ owing to its elevated carboxyl content, and lignin pyrolysis generated the most CH₄, which is characterized by a high higher heating value (HHV), as a result of its abundant aromatic rings and methoxyl groups. The bio-oil derived from cellulose was distinguished by the presence of unique saccharides and a higher proportion of furans, hemicellulose bio-oil was characterized by a predominance of acids and ketones, and lignin bio-oil was primarily composed of phenols (Zhao et al., 2017).

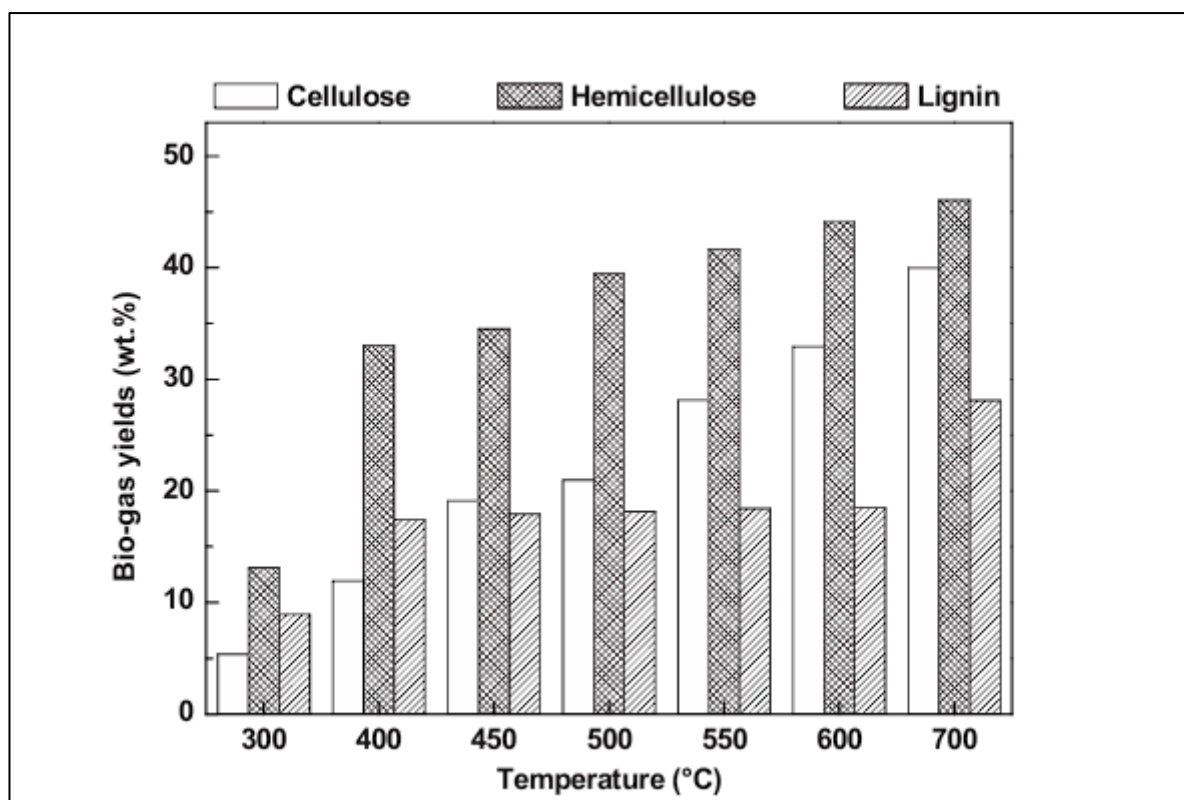


Figure F.1. Bio-gas yields (Zhao et al., 2017).

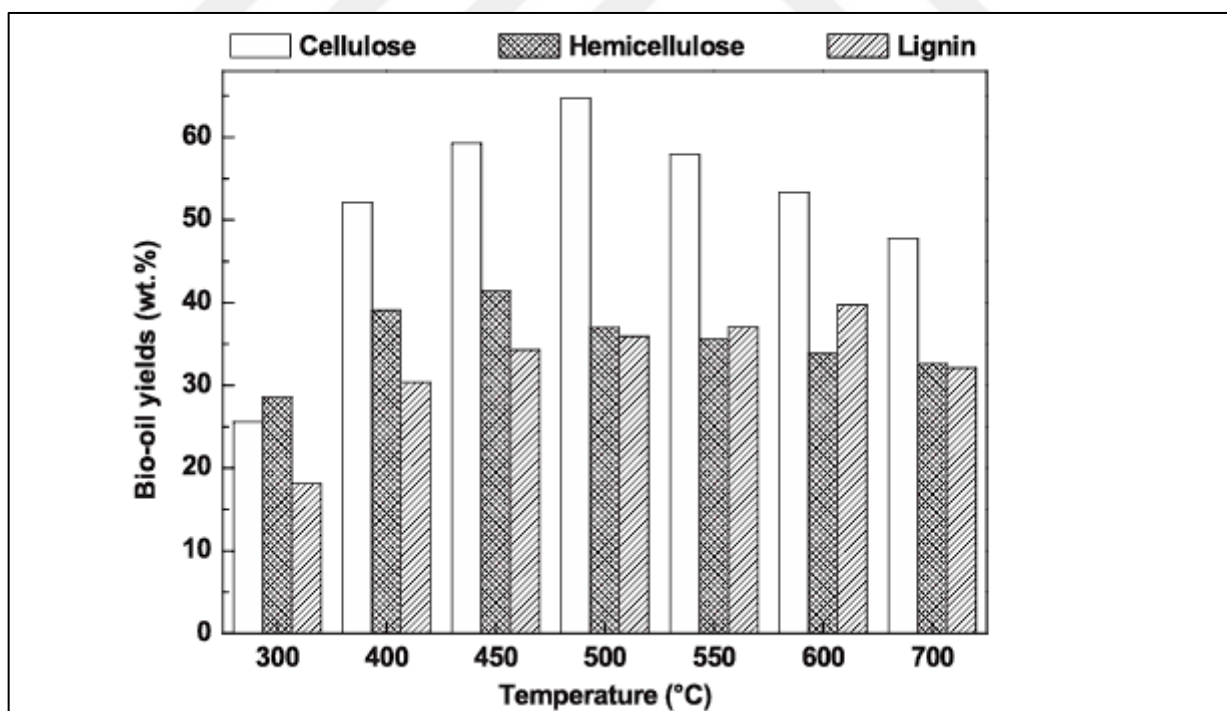


Figure F.2. Bio-oil yields (Zhao et al., 2017).

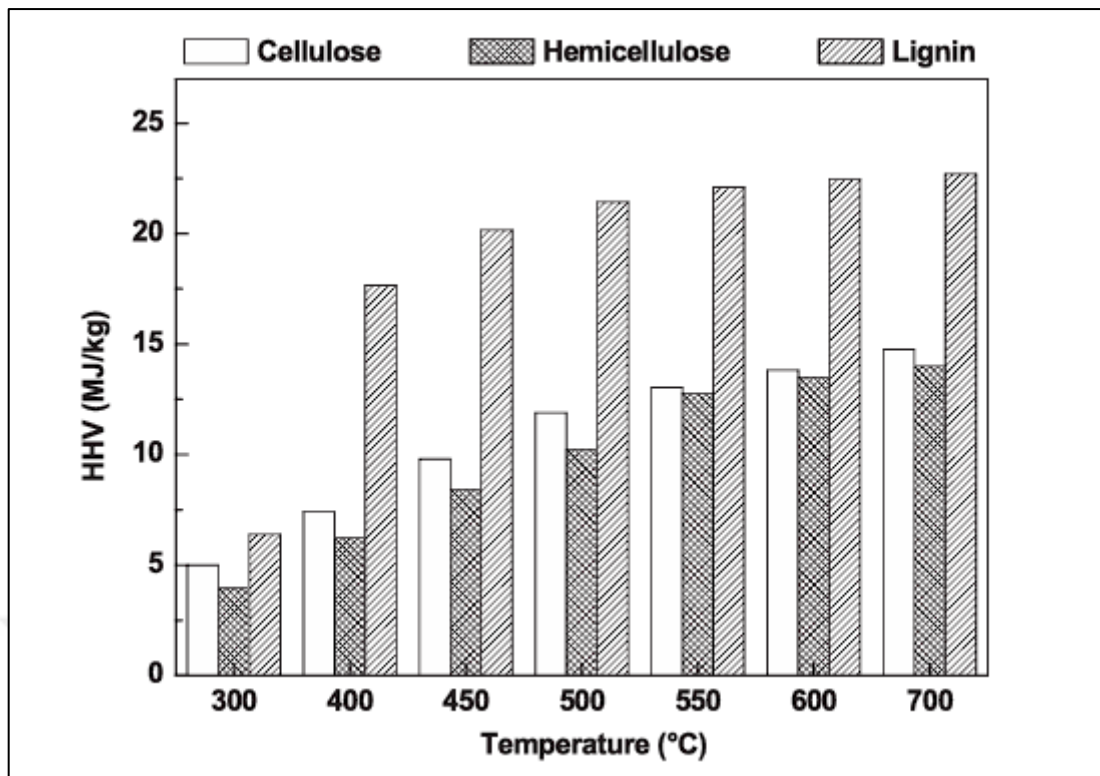


Figure F.3. The higher heating value of bio-gas at pyrolysis (Zhao et al., 2017).

According to Park et al. (2023) study, the elemental and proximate analysis for mixed waste wood is shown in Table F.1. (Park et al., 2023).

Table F.1. Elemental and proximate analysis of mixed waste wood (Park et al., 2023):

Feedstock	Element Analysis			Proximate Analysis			Composition Analysis		
	C (%)	H (%)	O (%)	Volatile Matter (%)	Fixed Carbon (%)	Ash (%)	Cell (%)	Hemi (%)	Lig (%)
Mixed Waste Wood	48.1	5.7	46.2	86.15	10.44	3.41	42.27	27.05	30.68

APPENDIX G: ANALYSIS AND IMPORTANCE OF PYROLYSIS OF LABEL WASTE

The composite label waste analyzed in this thesis consists of 85% cellulose-based coated paper and 15% polymer. The polymer fraction is composed of 50% plastic-based polypropylene and 50% plastic-based polyethylene. The elemental and proximate analyses of the composite label wastes used in this study were obtained from Yunus Tolunay Kılıç's thesis titled High Temperature Pyrolysis of Composite Wastes For Syngas Production (Kılıç. 2023).

Table G.1. The proximate analysis of label waste (Kılıç. 2023).

Feedstock	Moisture (%)	Volatile Matter (%)	Ash (%)	Fixed Carbon (%)
<i>Cellulose-Based Coated Paper</i>	4.65	75.10	17.45	2.80
<i>Plastic-Based Polypropylene</i>	0.20	98.40	1.30	0.10
<i>Plastic-Based Polyethylene</i>	0.20	99.20	0.59	0.01
<i>Composite Label Waste</i>	2.1	85.52	4.98	7.4

The composite label waste is good for pyrolysis because it has a high concentration of volatile matter (85.52%) and a relatively low concentration of ash (4.98%). These characteristics indicate considerable potential for the recovery of gas and liquid products during thermal processing. The low amount of fixed carbon (7.4% of the total waste) means that not much char is being formed, which is in line with the main goal of increasing syngas yield. Moreover, the moisture content (2.1%) is negligible, diminishing the energy needed for pre-processing and improving the overall efficiency of pyrolysis. The low-ash polymers mitigate the ash concentration, which the cellulose-coated paper predominantly affects, thereby reducing operational issues like slagging.

The comparison highlights notable differences among cellulose-based coated paper, polypropylene and polyethylene, and composite label waste. Polymers demonstrate exceptionally high volatile matter content, exceeding 98%, which is significantly greater than that of cellulose-

based paper (75.10%). This indicates that polymers are more reactive and have a higher potential for gas generation during pyrolysis. On the other hand, cellulose-based paper contains considerably more ash (17.45%) compared to polypropylene (1.30%) and polyethylene (0.59%), resulting in the composite waste having a moderate ash content of 4.98%. Also, cellulose has a higher percentage of fixed carbon (2.80%) than polymers, which have almost no value. This is one reason why the composite waste has a fixed carbon percentage of 7.40%. Lastly, while cellulose-based paper has the highest moisture level (4.65%), the polymers' moisture content is minimal (0.20%), leading to a balanced moisture level of 2.1% in the composite waste, which is favorable for pyrolysis efficiency.

Table G.2. The ultimate analysis of label waste (Kılıç, 2023).

Feedstock	Carbon (%)	Hydrogen (%)	Nitrogen (%)	Sulphur (%)	Oxygen (%)
<i>Cellulose-Based Coated Paper</i>	40.16	5.37	0.003	0.22	54.22
<i>Plastic-Based Polypropylene</i>	78.24	11.96	0.11	0.25	9.44
<i>Plastic-Based Polyethylene</i>	80.76	12.95	0.05	0.27	5.97
<i>Composite Label Waste</i>	59.13	8.5	0.52	0.05	31.8

The elemental analysis data for composite label waste components indicate the characteristics of various materials. Polypropylene and polyethylene, which are plastic-based, possess high energy density owing to their elevated carbon (%78.24 and %80.76) and hydrogen (%11.96 and %12.95) content. The elevated oxygen content (54.22%) distinguishes cellulose-based paper. The composite waste, including 59.13% carbon and 8.5% hydrogen, signifies a blend of plastic and paper components. The nitrogen and sulfur content is minimal (0.52% and 0.05%), indicating a favorable environmental effect profile. Plastic parts have a lot of energy potential, which means that composite label trash might be a good material for turning into energy in pyrolysis processes.

Coated paper made from cellulose has a low energy density, with 40.16% carbon and 5.37% hydrogen. Plastics made from polypropylene (78.24% carbon, 11.96% hydrogen) and polyethylene (80.76% carbon, 12.95% hydrogen) have higher energy potential. Cellulose-based paper contains a substantially higher oxygen content (54.22%) than plastics (PP: 9.44%, PE: 5.97%), suggesting that the oxygen is derived from cellulose. Composite label trash contains 59.13% carbon and 8.5%

hydrogen, indicating the properties of the amalgamation of cellulose and plastic components. The inclusion of the plastic fraction elevates the energy density of the composite waste above that of cellulose paper, although remains below that of plastics. Furthermore, all materials possess minimal nitrogen and sulfur content (below 0.52%), providing an environmentally sustainable character.

Table G.3. Calorific values of composite waste samples (Kılıç, 2023).

Waste	High Heating Values (MJ/kg)
<i>Cellulose-Based Coated Paper</i>	15.23
<i>Plastic-Based Polypropylene</i>	39.94
<i>Plastic-Based Polyethylene</i>	43.21
<i>Composite Label Waste</i>	27.12

High heating values (HHV) distinctly indicate the energy potentials of the materials. Plastic-derived polypropylene (39.94 MJ/kg) and polyethylene (43.21 MJ/kg) both exhibit significant energy density due to their elevated carbon and hydrogen composition. The elevated oxygen content of cellulose-based coated paper significantly reduces its HHV value to 15.23 MJ/kg. The high energy density of plastics and the low energy potential of cellulose come together in composite label trash, which has a value of 27.12 MJ/kg. This circumstance suggests that the plastic component substantially enhances the overall energy potential of composite trash, whereas the paper component considerably restricts this enhancement. From this point of view, composite trash is a framework that combines the great energy-conversion benefits of plastics in pyrolysis processes with the environmental friendliness of cellulose.

Conventional waste management techniques cannot effectively process cellulose- and polymer-based composite label wastes due to their intricate structures in recycling operations; however, pyrolysis can transform them into energy and valuable chemical products. Because it is mostly carbon. Cellulose is an important part of making biofuels. Polymers especially plastics like polyolefins and polystyrene turn into useful energy sources like hydrocarbon oils and syngas because they have high calorific values (Sharuddin et al., 2016). Bio-oils, syngas, LNG that come from pyrolysis can be used as carbon-neutral energy sources instead of fossil fuels and help recycle waste according to the principles of the circular economy. Literature indicates that products derived from pyrolysis substantially enhance energy security, minimize emissions, and promote sustainability in industrial applications; concurrently, future energy policies are anticipated to diminish reliance on fossil fuels by encouraging energy production from waste.