COMPARATIVE LIFE CYCLE ASSESSMENT OF PLASTIC (PET), GLASS, AND ALUMINUM CANS FOR SOFT DRINK PACKAGING IN ACCORDANCE WITH THE TRANSITION TO DECARBONISATION AND POLLUTION PREVENTION PRINCIPLES

by

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ABSTRACT

COMPARATIVE LIFE CYCLE ASSESSMENT OF PLASTIC (PET), GLASS, AND ALUMINUM CANS FOR SOFT DRINK PACKAGING IN ACCORDANCE WITH THE TRANSITION TO DECARBONISATION AND POLLUTION PREVENTION PRINCIPLES

Packaging materials have numerous applications in our daily lives and in industry. One of them is soft drink packaging products. Both in Turkey and the EU, packaging-related regulations, directives, and policies have been updated in accordance with circular economy and the EU Green Deal principles. The primary objective of this study is to assess the environmental outcomes associated with decarbonization, reuse, recycling, and recycled content targets by conducting an LCA across various scenarios for PET, glass, and aluminum. Initially, only for the pre-consumer stage, 2020 was set as the baseline scenario, where lower share of renewable energy and no recycled content were considered to produce the selected materials. With the increasing share of renewable electricity, 2035 and 2053 were targeted to improve both the pre-consumer stage by applying electrification and recycled content, and the post-consumer stage by supporting reuse and recycling. According to the selected impact categories, the thesis concluded that for the pre-consumer stage of each product, the use of recycled content, electrified processes and renewable electricity have favorable aspects under optimal conditions. Attention must be paid to the necessary efficiency and redesign points in renewable electricity generation and electrification process. In the post-consumer stage, the reuse process (especially for glass) can be promoted for resource conservation and energy efficiency by improving water consumption. Although the reuse of PET sounds more environmentally friendly, health concerns and product durability during consumption need to be considered and thus, for both aluminum and PET, recycling must be supported with some operational improvements.

ÖZET

KARBONSUZLAŞMAYA GEÇİŞ VE KİRLİLİĞİN ÖNLENMESİ İLKELERİ DOĞRULTUSUNDA GAZLI İÇECEK AMBALAJLARI İÇİN PLASTİK (PET) VE CAM ŞİŞELER VE ALÜMİNYUM TENEKELERİN KARŞILAŞTIRMALI YAŞAM DÖNGÜSÜ DEĞERLENDİRMESİ

Ambalaj malzemelerinin günlük hayatımızda ve endüstriyel olarak birçok kullanım alanı vardır. Bunlardan biri de gazlı içecek ambalaj ürünleridir. Hem Türkiye'de hem de AB'de ambalajla ilgili yönetmelikler, direktifler ve politikalar döngüsel ekonomi ve AB Yeşil Mutabakatı ilkelerine göre güncellenmiştir. Bu çalışmanın temel amacı, PET, cam ve alüminyum ambalaj ürünlerinin çeşitli senaryolar üzerinde YDA gerçekleştirerek karbonsuzlaşma, yeniden kullanım, geri dönüşüm ve geri dönüştürülmüş içerik hedeflerini dikkate alarak çevresel etkilerini yorumlamaktır. Başlangıçta, sadece tüketici öncesi aşama için, 2020 temel senaryo olarak belirlenmiştir, yani seçilen malzemelerin üretimi için geri dönüştürülmüş içerik dahil edilmemiştir ve ilgili yılın elektrik üretim verileri kullanılmıştır. 2035 ve 2053 yılları için yenilenebilir elektrik payının artmasıyla, seçilmiş proseslerde elektrifikasyon ve geri dönüştürülmüş içerik uygulaması sağlanarak hem üretim aşamasını hem de yeniden kullanım ve geri dönüşümü destekleyerek ürünün tüketim sonrası aşamalarını iyileştirmek hedeflenmiştir. Seçilen etki kategorileri bağlamında tez, her bir ürünün üretim aşaması için geri dönüştürülmüş içerik, elektrifiye edilmiş prosesler ve yenilenebilir elektrik kullanımının uygun koşullar altında olumlu yönleri olduğu sonucuna varmıştır. Yenilenebilir elektrik üretimi ve elektrifikasyon süreçlerinde gerekli verimlilik ve yeniden tasarım noktalarına dikkat edilmesi gerekmektedir. Yeniden kullanım süreci (özellikle cam için), yıkama (aynı zamanda geri dönüşümde de uygulanan) süreçlerinde su tüketimini iyileştirerek birincil kaynak tasarrufu ve enerji verimliliği açısından teşvik edilebilir. PET için yeniden kullanım aşaması ise daha çevre dostu görünse de tüketim sırasında sağlık endişeleri ve ürün dayanıklılığı bağlamında ele alınması gerekir. Ancak alüminyumda olduğu gibi PET için de geri dönüşüm, operasyonel iyileştirmelerle desteklenmelidir.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS/ABBREVIATIONS

Symbol	**Explanation**
\$	Dollar
Al_2O_3	Alumina
CH_4	Methane
CO_2	Carbon dioxide
Cu	Copper
g	Gram
HFC	Hydrofluorocarbons
kg	Kilogram
L	Liter
m^3	Cubic meter
mL	Milliliter
N_2O	Nitrous oxide
NH_3	Ammonia
Nm^3	Normal cubic meter
PFC	Perfluorocarbons
SO_2	Sulfur dioxide
W_m	Market Weight

Abbreviation	**Explanation**
BaU	Business-as-Usual
BOTAŞ	Petroleum Pipeline Corporation
CCS	Carbon Capture System
CE	Circular Economy
CEAP	Circular Economy Action Plan
CML	Centrum voor Milieukunde Leiden
DALY	Disability-adjusted Life Year
EBCs	Economic Boundary Conditions
EC	European Commission (For 94/62/EC, EC: European Community)
ECF	European Climate Foundation
EDAS	Evaluation based on the Distance from the Average Solution
EFSA	European Food Safety Authority

EG	Ethylene Glycol
EoL	End-of-Life
EOL-RR	End-of-Life Recycling Rate
EPR	Extended Producer Responsibility
ESI	Environmental Sustainability Index
EU	European Union
EUC	Environment, Urbanization and Climate Change
FEVE	European Container Glass Federation
GEN	Global Ecolabelling Network
GHG	Greenhouse gases
GWP	Global Warming Potential
HACCP	Hazard Analysis Critical Control Point
HDPE	High Density Polyethylene
IPC	Istanbul Policy Center
IPI	Imperfection Index
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LDPE	Low Density Polyethylene
LMDI	Logarithmic Mean Divisia Index
MCI	Material Circularity Index
MCF	Midpoint Conversion Factor
MENR	Ministry of Energy and Natural Resources
MFA	Material Flow Analysis
NMVOC	Non-methane volatile organic compound
O.G.	Official Gazette
PET	Polyethylene terephthalate
PPWR	Packaging and Packaging Waste Directive
PTA	Purified Terephthalic Acid
PWCR	Packaging Waste Control Regulation
R&D	Research & Development
RefPET	Refillable PET
RES	Renewable Electricity Sources
rPET	Recycled PET
SDG	Sustainable Development Goals
SETAC	Society of Environmental Toxicology and Chemistry

SWOT	Strengths, Weaknesses, Opportunities, and Threats
EU	European Union
TSS	Technical Suitability for Substitution
TUIK	Turkish Statistical Institute
UBC	Used Beverage Can
UNDP	United Nations Development Program
UNEP	United Nations Environment Program

1. INTRODUCTION

Attempts at life cycle analysis date back to the 1970s. First, Limits to Growth (Meadows and Club of Rome 1972) was published in 1972. Then, predictions about the limitations of resource availability and the concept of the "limit to growth" approach were disseminated by the Club of Rome. Subsequently, the oil price shocks and the energy crisis in 1973 triggered an analysis of this issue. In this regard, there were focused on quantitative analyses of environmental problems and pollution (air, land, and water pollution). Thus, the methodological work started with the analysis of packaging products, but it was realized that this topic has a much broader aspect. With this awareness, the application of these analytical studies within economic sectors has begun. During the development of LCA, three leading organizations have emerged, namely ISO (14000 standard series), UNEP, and SETAC (Jolliet et al., 2020). On one hand, LCA has significant importance for analyzing environmental impacts; on the other hand, in terms of corporate sustainability, this concept is crucial to the decision-making process (Verghese et al., 2012).

Furthermore, circular economy, a regenerative approach that can be related to various aspects of the study, was initially defined by Pearce and Turner in 1990 (Peña et al., 2021). According to their definition, circular economy is an economic model that utilizes waste as a resource and incorporates it into economy. In this model, the consumption and production patterns, which relate to SDG 12, are crucial because unsustainable production and consumption cannot meet the requirements of circular economy. Here, the basic process involves using less and reducing waste generation accordingly (Peña et al., 2021). That is to say, the basic principles of CE can be sorted as follows: (1) waste and pollution generation must be at the minimum possible level, (2) the product obtained again should be of high quality, (3) regeneration of ecological and natural systems must be protected (Ellen MacArthur Foundation Project Team, 2015). Moreover, a novel approach, as presented in Figure 1.1, 9R (R0 to R9) framework, is a must-adapted approach for the proper implementation of circular economy (Hirsch & Schempp, 2020; Kıran Cılız et al., 2022; Okorie et al., 2018). With an extensive set of impact categories and an interdisciplinary approach, the life cycle model provides holistic outcomes for decision-making (Zamagni et al., 2013). In short, the incorporation of LCA into CE brings a novel perspective on desirable changes in consumption and production patterns (Kıran Cılız et al., 2022; Peña et al., 2021).

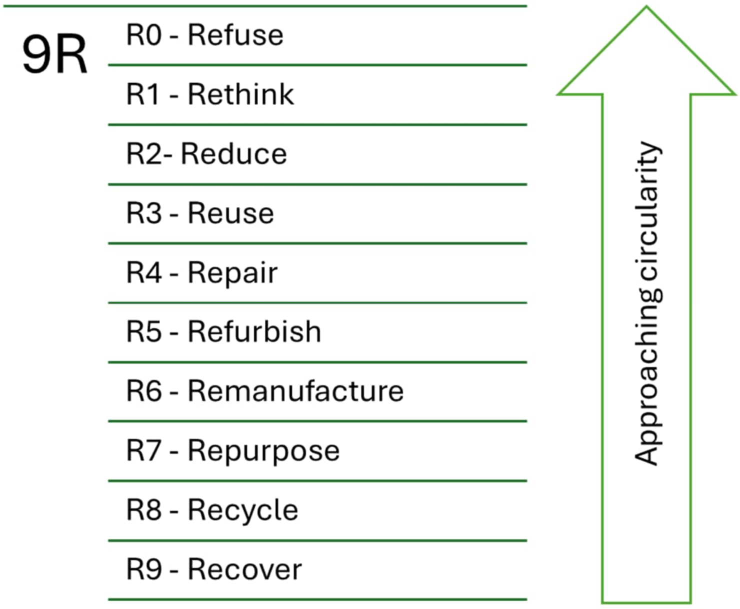

Figure 1.1. 9R Principles Framework

Packaging materials serve multiple functions, including preservation, distribution, and intermediate functions, among others, for products and services. Therefore, many industries seek quantitative methods to assess the environmental impacts of the steps involved in the production, packaging, processing, transportation, and waste management of packaging materials (Šerešová & Kočí, 2020). One of the methods employed at this stage is the product life cycle, as outlined in ISO 14040:2006 and ISO 14044:2006. With the product life cycle, comparative results can be accomplished by measuring values such as resources and raw material use, energy consumption, and greenhouse gas emissions (Banar & Cokaygil, 2008; Bertolini et al., 2016; Brock & Williams, 2020; Pragati & Maeda, 2023).

As the world population is expected to reach around 9.7 billion by 2050, efforts should be made to ensure SDG-12, Sustainable Consumption and Production, given the increasing population (Food and Agriculture Organization of the United Nations, 2017; United Nations, 2022). While approximately 35% of municipal solid waste in Western Europe consists of packaging materials, the amount of packaging waste is increasing as income levels rise and lifestyles change. In other words, the volume of packaging waste generated in developing countries is likely to increase (Worrell, 2023). Therefore, companies, institutions, and organizations must consider the environmental impacts of the post-consumption fate of beverage packaging (Beltrán et al., 2024).

From an energy-relevance perspective, renewable energy transition is another significant factor on the path to decarbonization. The use of fossil fuels in electricity generation remains a vital global concern. Turkey, on the other hand, has adopted a policy of increasing the use of renewable energy, as evident in its energy policy aimed at reducing its dependence on fossil fuels (Ministry of Energy and Natural Resources, 2022). Accordingly, it seeks to reduce GHG emissions across all sectors to achieve the 2053 net-zero targets. The issue of renewable energy must be addressed in consideration of both its favorable and unfavorable aspects and dealt with according to the most appropriate conditions of the relevant region. In other words, although renewable energy is a prominent component of the green transformation, it must meet the country’s socio-economic, geopolitical, infrastructural, knowledge and R&D requirements (Ari, 2023; Sahin & Esen, 2022; Zaimoğlu & Pehlivanzade, 2023).

The primary objective of this study is to interpret and analyze the most environmentally sustainable and optimum results of soft drink packaging products in line with current targets and practices, using Life Cycle Assessment (LCA). Furthermore, within the scope of the study, life cycle impact assessments were conducted for the pre-consumer and post-consumer stages of soft drink packaging materials, based on a functional unit of 1 million and 2020 (baseline), 2035 and 2053 (net-zero target) years. In addition, to evaluate the individual effects of reuse and recycling, a sensitivity analysis was performed for PET and glass packaging materials. Accordingly, along with the scenarios identified for the study, other necessary scientifically based information is provided in detail. These are, in turn, literature review, methodology, results and conclusion. In the application of LCA, the points mentioned above are linked to it. During this practice, the primary criteria, as outlined by the principles of circular economy (rethink, redesign, recycle, and reuse), and the use of recycled content were taken into account. At the end of the study, the scenarios were interpreted and discussed in detail.

2. LITERATURE REVIEW

2.1. Comparative Studies Measuring Environmental Impacts of Soft Drink Beverage Packaging

Many conventional and comparative studies have been conducted on soft drink and carbonated beverage packaging to determine which material is more environmentally sustainable in terms of specific environmental impacts. In the first section of the literature review, I aim to synthesize literature-based case examples from comparative studies.

Initially, one of the studies addressed all stages of carbonated beverage packaging, including 0.5 L and 2.0 L PET bottles, 0.33 L aluminum cans, and 0.75 L glass bottles. For each volume and packaging type, these stages are packaging, ingredients, manufacturing, waste management, and transport. That is to say, consideration of the manufacture and filling of the beverage itself is also a noteworthy point of the study. Moreover, in the sensitivity analysis section, the reuse system for 0.75 L glass bottles was incorporated into the study, and the retail (refrigeration) stage was considered for 0.5 L PET and 0.33 L aluminum cans. For the study, the CML 2001 method was employed, and upon analyzing the GWP impact, one of the primary indicators of climate change, it is evident that the packaging process has a significant impact, accounting for an average share of 65-70% among the processes examined. In addition, other prominent implications include the reduction of GHG emissions when the recycling rate is appropriately implemented and the reuse rate for glass products (including transportation and washing stages in the system) is increased (Amienyo et al., 2013).

Secondly, another research is notable due to its multifaceted and detailed considerations. With several combinations of EoL options, more understandable and comparable results are available for waste management viewpoints. Also, within the scope of the study, the analyzed materials are PET, PLA, glass, aluminum, and cardboard. However, the focus of my research was PET, aluminum and glass. To point out, in this examination, the main inference is the importance of waste collection before determining how to treat waste (Simon et al., 2016).

The study utilized the database of GaBi 4 software, as well as additional databases and international studies, in compliance with ISO Standards (ISO 14040:2006 and ISO 14044:2006) (Simon et al., 2016). When examining the on-site production process with equal volume values for each product, i.e., the environmental impact of 0.5 L PET, glass, and aluminum beverage packaging types, the environmental impact of glass, aluminum, and PET bottles is in the order from highest to lowest, respectively. Numerically, when we consider 0.5 L products as 1000 L functional unit, these values are 582.9, 449.5, and 325.8 kg CO2-equivalent emissions for glass, aluminum, and PET, respectively. When the recycling process is analyzed, the order of impact remains unchanged, but the amount of environmental impact decreases for each product, as shown in Figure 2.1. The term credit mentioned in Figure 2.1 refers to the environmental impact that can be avoided by choosing the use of secondary material over the use of primary material (Simon et al., 2016). Compared to this LCA practice, MFA-based research analyzed and discussed four material types: PET, glass, aluminum cans, and cardboard. Aligning with the waste management perspective, the post-consumer stage reveals how it changes the fate of environmental impacts. For all materials, among the options of landfill, incineration and recycling, the last one (recycling) is the most favorable option in terms of waste management (Amicarelli et al., 2024).

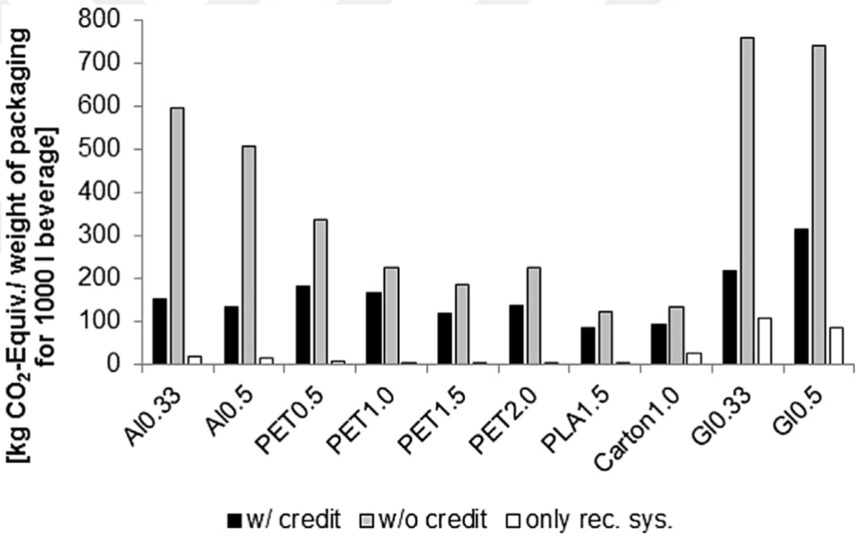

Figure 2.1. GHG impact of the recycling system (kg CO_2 equivalent)

On the other hand, a refill can be referred to as the reuse of a product because, under this circumstance, the material is not reprocessed chemically, mechanically, or biologically. Significant emphasis is placed on the refill of water, chemicals, and energy used for the material during washing and distribution (Simon et al., 2016). Outcomes revealed that the reuse system can remarkably decrease GHG emissions. The reuse system for beverage packaging materials must be thoroughly and properly defined from the consumer's perspective. In other words, if the rate of reuse is kept high, the material circularity speed has to be arranged for consumers.

Another LCA study evaluated only two materials – PET and glass. The key point here is to emphasize the importance of glass bottle returnability. This study is significant for the post-consumer stage, specifically in the context of waste management. In addition, although secondary data was used in the study, primary data was also used. It is also essential at this point to adapt the primary data for LCA to the relevant study. Within the scope of waste management, scenarios were created separately for two different products, with an emphasis on the points where these scenarios differ. To clarify, this is recycling for PET and returnability for glass. For glass beverage packaging, a 95% return rate was considered acceptable for washing. In this case, PET beverage packaging outperformed in 9 categories out of 15. When emphasizing returnability, it becomes clear that the damage impacts of glass can be mitigated (Boutros et al., 2021).

Single-use and returnable glass bottles were also compared through a direct LCA study. In terms of data use, the use of primary data was taken into consideration. In the scenario for reuse, the bottles were subjected to the following steps: washing with hot water and chemicals (detergent, release agent for labels, acid product, and disinfectant), filling with water, capping, labeling, and packaging for distribution (Tua et al., 2020). For the reuse scenario, the refund rate was assumed to be 98.69%, and the loss rate was assumed to be 1.31% for each delivery (this portion was assumed to be recycled). As a result of this study, at least 4 times reuse should be preferred (Tua et al., 2020); indeed, the ideal number of reuses is 7-9 (Simon et al., 2016).

An additional study did not directly apply LCA; however, the results can be relatable to the LCA of the selected soft drink packaging materials. When shed light on this study, the authors calculated and interpreted ESI results. Additionally, although the survey encompasses three product types, it yields informative outcomes on how the recycling and reuse of glass are changing the tide, and results are also available for comparing the manufacturing processes of each selected packaging material (Almeida et al., 2017). Like the previous study (Tua et al., 2020), this study emphasizes the efficiency of reusing and recycling glass bottles (Almeida et al., 2017). The starting point of ESI calculation is emergy and the emergy term was calculated in the solar energy unit (Almeida et al., 2017). After various calculation stages, the ESI value, which is unitless, was calculated to compare the selected beverage packaging materials in different scenarios. The amount of material required for a 1000 L beverage was selected as the functional unit. The calculated values for the study are illustrated in Figures 2.2 and 2.3 below. In addition, within the scope of this study, recycled PET refers to a PET bottle made from 40% recycled material by weight, and also, sending glass bottles to washing for reuse was taken into account. Relevant varying definitions for glass bottles were provided in Table 2.1. The study also proved that recycling and reuse reduce environmental impact (Almeida et al., 2017).

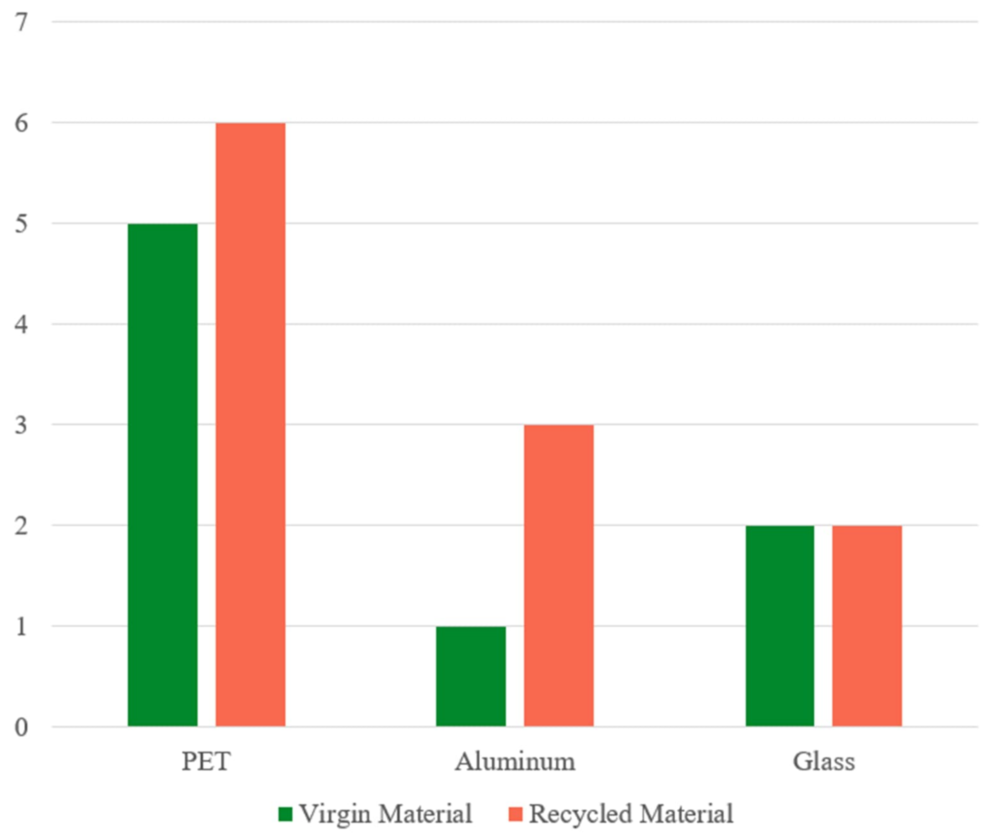

Figure 2.2. ESI values for the selected materials (based on the virgin and recycled material)

Table 2.1. Material definitions for glass material

Material	**Definition**
Glass	Glass produced from primary raw material
Glass 20	Glass reused 20 times
Glass-R	Glass made from 25% recycled material by weight
Glass-20R	Glass produced with reuse and then recycling

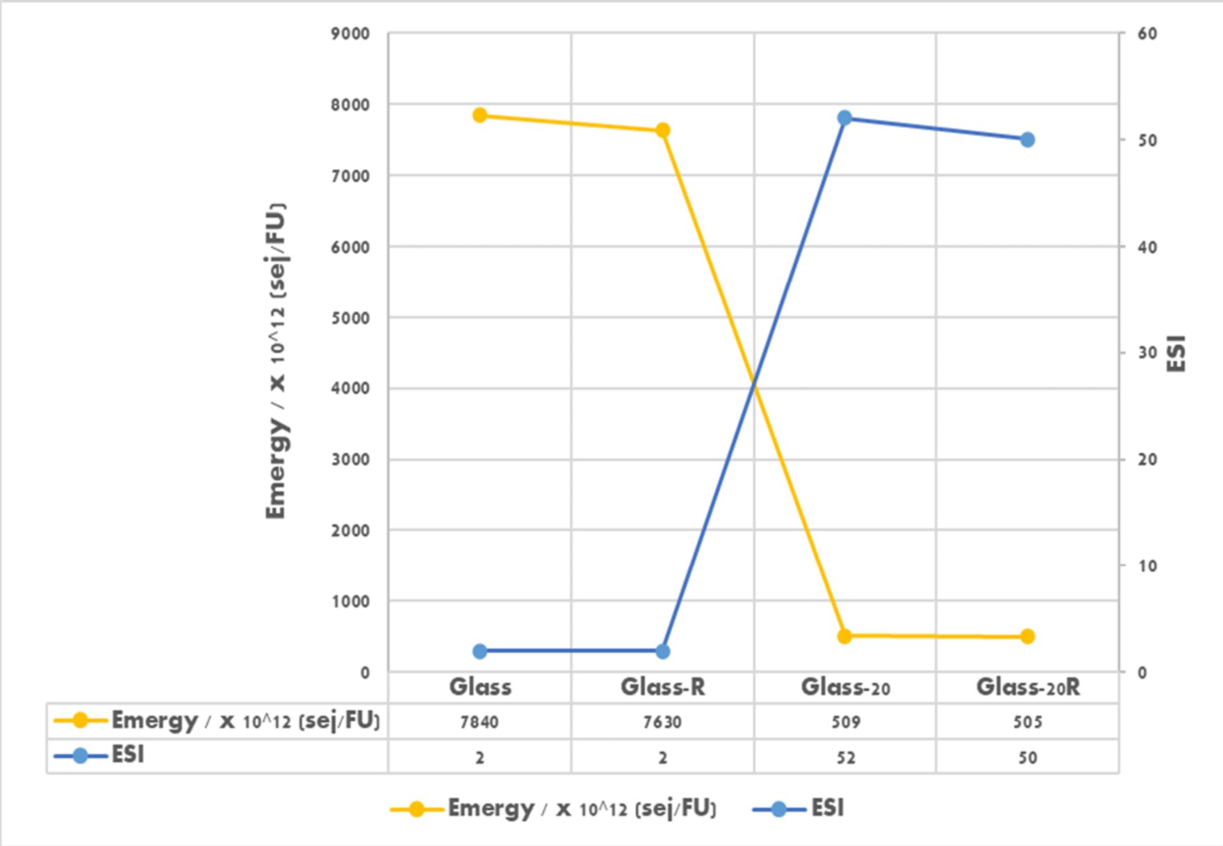

Figure 2.3. For the relevant scenario, glass ESI and emergy values

Similar to the previous study, Ferrara et al. (2021) conducted an analysis based on a comparison of post-consumer impacts. According to this study, the ReCiPe 2016 v1.1 (Hierarchist) impact assessment method, which includes both midpoint and endpoint impact categories, was used to measure the environmental impacts of 1 L (functional unit of the study) PET and glass bottles (Ferrara et al., 2021). With the latest update of the ReCiPe method, it is not limited to Europe but has the feature of being representative as a characterization factor on a global scale (Huijbregts et al., 2017). In addition, the endpoint impact categories are basically grouped under three macro areas called Human Health Damage [DALY] (the impact of a person's life expectancy on years and provides quantitative data on the duration of years lost or years of disability resulting from disease or accident), Ecosystem Quality [species.yr] (species loss in terrestrial, freshwater and marine ecosystems within the period of time) and Resource Scarcity [$] (the additional cost that arises from future fossil resource or mineral extraction) (Ferrara et al., 2021; Huijbregts et al., 2017). Within the scope of the study, 18 midpoint impact categories and three primary endpoint impact categories were assessed. The authors highlighted the reuse of glass bottles (approximately six times) and the use of recycled PET resin in PET bottle manufacturing (Ferrara et al., 2021).

2.2. Deposit Refund System

The process of deposit refund system, that is one of the main scopes of the recycling system, can be simply defined as follows: There is a temporary fee for the packaging of the beverage when purchasing that beverage and then this fee is paid back to that person in case the packaging is returned and brought to the collection point (Görgün et al., 2021).

Deposit management system can make plausible and desirable results in many aspects, if it is implemented regularly and adequately. These results are important not only from an environmental perspective but also to ensure social and economic sustainability. To clarify these points, the collection of materials is conducted in a clean and orderly manner, ensuring efficient resource management and achieving circularity accordingly. A clean collection of materials is also important in maintaining high-quality recycled materials (Görgün et al., 2021).

On the other hand, separating the scrap materials – namely, source separation - after consumer use at the best level at the source directly affects the efficiency of recycling. In other words, scrap material should preserve its original and existing quality, because this is highly significant for the material to be reintroduced into the production process as a raw material (Görgün et al., 2021).

Considering the situation in Turkey, various studies have shown that the source separation process is not provided at an adequate level (Görgün et al., 2021). According to TUIK's quantitative data, in 2019, Turkey spent nearly $117, $1.88 million and $183 million on importing plastic, glass, and aluminum scrap materials, with approximate currency values of 2019, respectively (Görgün et al., 2021). Furthermore, in Turkey, deposit refund system application plays a crucial role in achieving the Sustainable Development Goals of the UNDP (Görgün et al., 2021).

Turkish Environment Agency, under the Ministry of Environment, Urbanization and Climate Change, plans to implement deposit management system in 81 provinces of Turkey by the end of 2025. This system will align with the Zero Waste plan and provide incentive payments to citizens. With this method, as shown in Figure 2.4 below, source separation can be applied by inserting beverage packages (PET, glass and aluminum) with the emblem of deposit into deposit machine. As a result of this system, steps towards the use of secondary raw materials, reduction in the use of energy and primary raw materials and the 2053 Net Zero targets can be taken (Ministry of EUC (Access date: 05/03/2025), n.d.).

Figure 2.4. DRS symbol and DRS machine

In 2022, deposit return system was piloted in Kızılcahamam, Ankara, Turkey. The study was conducted to analyze the applicability of deposit refund system for beverage packaging material types (PET, glass and metal). The study period selected for the investigation is from July 2022 to December 2022 (6 months) and five different collection areas were allocated (Tasarsu & Eren, 2023). It is a valuable approach to conduct the study in various locations with defined boundaries and periods. Different amounts of waste were collected from multiple locations, depending on consumption habits and regional populations. Glass products were collected in the highest mass quantities, as this is a mass-based study and the mass of an individual glass product is higher than that of PET and aluminum. Still, a further analysis in terms of the number of products should also be provided. In terms of results, waste collection data is only possible for 1 location (National Garden) for six consecutive months. As shown in Figure 2.5, the waste collection rate for this location has shown a rapid increase over the past six months of 2022 (Tasarsu & Eren, 2023). Subsequently, DRS can increase the collection and thus recycling rate; however, awareness, policy, and infrastructural-related measures should be taken.

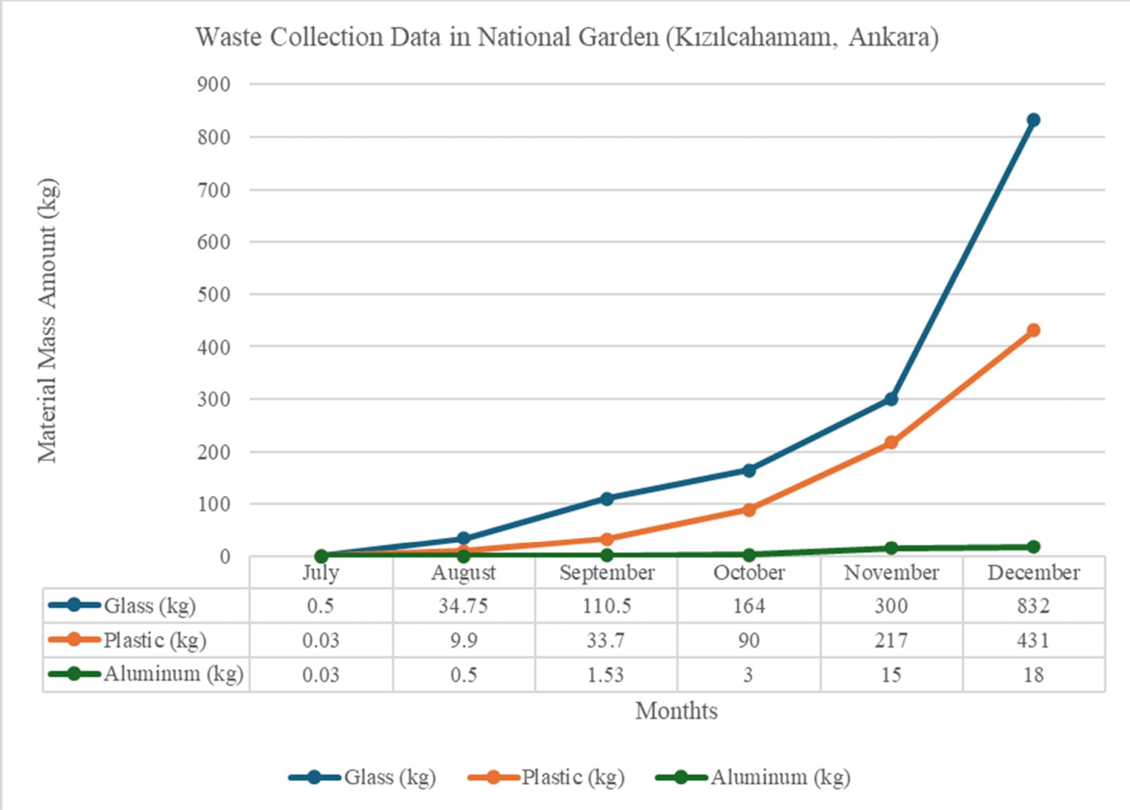

Figure 2.5. Waste collection data in National Garden (Kızılcahamam, Ankara)

From further perspectives, the pros and cons of DRS were evaluated by an author (Lakhan, 2024). The study provided both a quantitative and qualitative analysis, i.e., a mixed analysis, to comprehensively address the issue of DRS. In the previous Ankara case study, the increase in the amount collected for each product over time can provide insight into consumer attitudes and is also informative, given that it is a local study. The study with mixed analysis is more comprehensive than the Ankara study, but it is insightful in its own right, as its purpose and scope differ from those of the Ankara study. The study, which employed both qualitative and quantitative analyses, is a meta-analysis study. The conclusion was drawn by compiling studies from a specific period in quantitative terms. Quantitatively, recycling rates and the economic costs associated with DRS were considered. Qualitatively, consumer behavior, stakeholder resistance, policy consistency and stability, and adaptability to changing conditions were also taken into account. Some of the problems associated with these factors were also summarized in this study. These include fraud and illegality, resistance from stakeholders, high operational and administrative costs, keeping pace with technological and consumer behavior changes, and coherent and stable policy and regulatory enforcement. Although meaningful inferences can be drawn from the study, the different designs of the included studies have affected the comparison of results, as stated by the author. The study period spanned from 2000 to 2024, and 45 studies from 20 countries worldwide were selected (Lakhan, 2024).

In addition, providing possible and feasible solutions to each long-term challenge can be compromising for decision-making. This study compiled the factors affecting DRS and their linkages to the challenges that may be encountered in DRS, as well as their possible solutions. This compilation is based on the quantitative and qualitative factors mentioned above. Increasing consumer involvement can lead to a higher rate of return (Lakhan, 2024). Firstly, examples from Norway and Switzerland can be used to encourage and thus increase consumer participation. Norway, with an application named Infinitum, allows collection points to be easily located and provides access to new updates on the subject. For Switzerland, the example of curbside recycling programs from the integrated waste management system can be given (Hage et al., 2018). While the Norwegian example can enhance society's contribution to DRS through technological advancements, the Swiss example can alleviate logistical burdens and enable greater flexibility for retailers. Secondly, uncertainties can be eliminated by establishing an appropriate and stable policy to provide a clearer path for stakeholders. Thirdly, the process can be made easier to manage by providing the proper policy guidance in economic terms, for example, through public-private partnerships and reliance on international development funding. Ultimately, taking a holistic approach suggests that DRS can be beneficial in the long term (Lakhan, 2024).

The recycling quality should also be discussed in the literature review, and, in this respect, a detailed and comprehensive study was included. This is one of the noteworthy studies that can serve as a basis for other future studies and the study on quantitative recycling quality addressed this framework at three basis points, as shown below (Roosen et al., 2023):

- Virgin Material Displacement Potential is the potential to use secondary raw material. In addition, special calculations were made for the following points, which are sub-items of this aspect (Roosen et al., 2023).

    1) TSS: TSS is related to whether the secondary substance technically has specific defined properties. These features are mainly: Mechanical properties, workability, aesthetic properties, chemical load, and legal restrictions. If the TSS value is 0, the product is of unsuitable quality; if the TSS value is 1, the product is of suitable quality. In cases where the TSS value is less than 0 and greater than 1, blending should be made with primary raw materials (Roosen et al., 2023).

    2) W_m: While the TSS value provides information about the properties of the material, W_m gives a value in terms of the scale about how many substitutions will be made. The more secondary material is available, the more desirable this situation is (Roosen et al., 2023).

3) EOL-RR: This point is related to how convenient the recycling industry and the application methods for recycling are. When considering the quality-quantity trade-off in relation to waste management, preventing loss in the amount of recycling also reduces the dependency of primary raw materials (Roosen et al., 2023).

4) EBCs: Economic Applicability of the recycling pathway (Roosen et al., 2023)

- The second term, In-Use Stocks Lifetime, is related to the amount of stock that can be used for society within a certain period. The focus here is on circular economy and access to raw materials, as well as the importance of time in circular economy (Roosen et al., 2023).

- Environmental Impact: The environmental impact in this study refers to recycling. This impact is directly related to LCA, but this study is limited to Carbon Footprint calculation for the sake of a simplified method (Roosen et al., 2023).

- Distance-to-Target Calculation: To measure this value, unitless numbers are obtained by calculating the above three aspects (Roosen et al., 2023).

As a consequence, some quantitative results were calculated for PET and glass. For both PET and glass, the suitability of various scenarios was ensured by distance-to-target calculation. For PET, scenarios for mechanical and chemical recycling of the product in the form of bottles, fiber and tray materials were created. The most two favorable scenarios are bottle-to-bottle mechanical recycling and bottle-to-fiber mechanical recycling, with distance-to-target values of 0.96 and 0.98, respectively. Secondly, when analyzed for the glass product, scenarios were made within the scope of reuse and remelting (i.e., recycling) for container, domestic and flat glass types. When examining the bottle and container glass products, it is proven that the glass materials collected and recycled through deposit return system demonstrate compliance in terms of environmental and product quality, with a distance-to-target value of 1.05 (Roosen et al., 2023). Besides these conclusions, recycling, extended producer responsibility, awareness and improvements in waste management technologies are significant factors to consider in the context of electricity generation. Ultimately, although the study has room for improvement, it is insightful and promising as it provides quantitative comparative results.

2.2.1. PET Reuse and Recycling Options

2.2.1.1. PET Reuse (Refillable PET – RefPET). The EU has targeted to shift to refillable PET bottles. The primary concerns about the reusability (refillability) of PET bottles are their durability and health concerns (European Union, 2025). Even if environmental impacts can be quantified, the longevity of PET products and their human health impacts must also be considered.

Firstly, from an environmental perspective, a study proved that the reusability of PET products can reduce the environmental burden. This study evaluated the environmental impact of one-time reuse, recycling and landfill of a 500 mL PET bottle. This study demonstrated that energy use and consequently CO_2 emissions were reduced by 40% to 45% with the reuse process compared to the recycling option. However, these results may vary depending on the operational processes and how the relevant process is handled (Hamade et al., 2020).

Secondly, another practice measured the durability and longevity of plastic products (including PET). This practice consists of three major phases: micro-indentation measurements, scratch tests, and experiments simulating reuse wear and washing. Some of the key findings of this study include investigating how washing conditions affect the durability (wear effect) of polymer products, such as PET, and developing suitable additives to enhance the scratch resistance of these products. Additionally, it offers advanced designs to improve the product's longevity in terms of reusability. According to this study, as well as others, concerns about the health effects of using reusable PET packaging material must be considered and addressed (Tenhunen-Lunkka et al., 2024). Thus, the reuse of PET bottles requires close attention from the HACCP plan and EFSA (Lemos Junior et al., 2019; Petcore Europe Reuse Working Group, 2023).

2.2.1.2. Selected PET Recycling Options. In literature, various innovative and topical studies have been recently conducted. As mentioned earlier, the recycling of PET bottles can be handled through open-loop recycling and closed-loop recycling; mechanical recycling, and chemical recycling. Additionally, mechanical recycling of PET bottles is more prevalent (Chairat & Gheewala, 2023).

One of the recent studies stated that fiber production is a common open-loop recycling application of PET bottles. By implementing proper recycling techniques, it is possible to reduce GHG emissions and primary resource consumption. Moreover, the manufacture of value-added products can be enabled. However, the quality of recycled content plays a significant role in its use, particularly in terms of human and environmental health, as well as the longevity of the product. For textile-specific use, major indicators are strength, stretching, surface roughness, IPI, and hairiness of the yarn

(Hossain et al., 2024). Additionally, several other factors, including the yarn manufacturing method, yarn composition, and blending proportion, should be taken into consideration.

On one hand, the crystallinity and tensile strength of recycled polyester fibers are lower than those of virgin ones (Hu et al., 2020). Increasing the use of recycled polyester does not alter the transmission properties of the fabric such as air permeability and moisture vapor permeability. Furthermore, it can increase the shear and bending stiffness of woven fabrics (by an average of 36% and 18%, respectively) (Hossain et al., 2024).

On the other hand, a recent study has examined PET-to-fiber production in detail under various scenarios. In this study, LCA methodology was applied, utilizing r-PET, virgin PET and cotton fiber in multiple cases to produce denim fabric. By adopting the EDAS approach, this study can determine which result is not optimal in relative terms. Specifically, it is also important for the researcher to emphasize why allocation should be avoided in LCA. In this examination, scenarios were made by using literature-based methods to address the challenges of allocation. These methods are (1) cut-off and (2) waste valuation methods (Fidan et al., 2024). Approach (1) treats primary and secondary products separately, i.e., as different systems (Hopewell et al., 2009; Shen et al., 2010). In other words, the process related to the primary product, including raw materials, is treated separately. There is only one end-of-life stage, which is defined for the secondary product (Frischknecht, 2010). In contrast, approach (2) assesses the environmental impact of the raw material across the life cycles of both the primary and secondary products (Shen et al., 2010). In fact, the ecological implications of unused and unwanted products (characterized as waste) are allocated to both processes (Shen et al., 2010).

The reference scenario for the study is based on the use of 85% Cotton and 15% rPET for the cut-off allocation method type. According to the EDAS values calculated based on both LCA and LCC (Life Cycle Cost), overall, out of the eight scenarios, the five scenarios ranked from the most favorable to the least are as follows (Fidan et al., 2024):

1) 100% rPET (cut-off)
2) 50% virgin PET + 50% rPET (cut-off)
3) 100% virgin PET (cut-off)
4) 50% virgin PET + 50% rPET (waste valuation)
5) 100% rPET (waste valuation)

Although similar results were reached in a different study, rPET can be utilized in certain proportions. This study evaluated the mechanical properties of fabrics produced using rPET under various scenarios. This evaluation is based on the use of various proportions of cotton, virgin PET, and rPET. Certain conclusions can be drawn from this study. The first one is that the quality of the fabric produced with rPET fibers is lower than that produced with virgin PET. However, secondly, it was shown that the use of rPET fibers to a certain extent does not significantly affect product quality and optimal results were achieved. For instance, blending rPET and cotton (the share is %30 and 70%, respectively) can enhance the pilling degree and bursting strength. The purpose of the use of the material can vary, so that the share of rPET, cotton and virgin PET changes according to that and, indeed, the relevant standards must be met. Consequently, the authors of the study highlighted the importance of upgrading recycling efficiency to improve material quality and reduce environmental burdens (Telli & Özdil, 2015).

When it comes to reviewing both open-loop and closed-loop recycling techniques, the study on PET bottle mechanical recycling is crucial to analyzing both bottle-to-bottle and bottle-to-fiber recycling (Chairat & Gheewala, 2023). The outstanding feature of this study is that it was carried out by considering LCA with MCI. Table 2.2 below provides MCI values for bottle-to-bottle and bottle-fiber. In the baseline scenario of bottle-to-bottle recycling, the worst collection rate was 31% while the best was 62%. Besides, MCI results also indicate that closed-loop recycling is more feasible than open-loop recycling in terms of material quality, but downcycling occurs over the course of time. Bottle-to-bottle recycling can be achieved nearly ten times (Chairat & Gheewala, 2023; Pinter et al., 2021). As long as material quality does not meet the standards for consumer use, bottle-to-bottle recycling must be ceased. At this point, bottle-to-fiber recycling can be practiced and this scenario can be arranged according to any specific case. Bottle-to-bottle recycling is preferable over bottle-to-fiber recycling in terms of material quality, aligning with the principles of circular economy (Chairat & Gheewala, 2023).

Table 2.2. MCI results for closed-loop and open-loop recycling

Bottle-to-Bottle		Bottle-to-Fiber	
Baseline Scenario	100% Collection Rate - 25% and 35% recycled content	Baseline Scenario - 100% recycled PET as a feedstock	Applicable maximum MCI rate
0.20-0.31	0.55 – 0.60	0.52	0.70

2.3. Renewable Electricity Generation in Turkey

The fundamental of Turkey's 2053 target is based on the climate crisis and our country has some commitments on this issue. With the approval of the Paris Agreement in 2021, a commitment was made to achieve 'net zero emissions' as a target for the year 2053 in order to combat the climate crisis (Gurcam, 2023). Especially, the climate-related natural disasters that occur due to the deterioration of the natural balance, as well as the potential effects of the European Union's Green Deal on our country's economy, highlighted the importance of measures to address the climate crisis (Gurcam, 2023). Moreover, within the scope of net-zero targets, these encompass various fields primarily including production processes, agriculture, energy, waste management and transportation (Akçali et al., 2023).

For the transition to renewable electricity as a significant step towards decarbonization, a compilation of relevant literature can be provided, aligning with current studies on this issue. Two different studies that were conducted with the LMDI method for Turkey support the transition to renewable energy. One common point between these two studies is that they investigated whether renewable energy is beneficial and feasible in the long run, specifically for Turkey's net-zero target, based on electricity generation between 2008 and 2020 (Ari, 2023; Sahin & Esen, 2022). In particular, one study employed a life cycle approach (Sahin & Esen, 2022), which further supports the current research in this regard. Figure 2.6 below shows the extent to which GHG emissions change depending on the shift in renewable and non-renewable energy use between 2008 and 2020 (Sahin & Esen, 2022). The primary emphasis of the study is that the transition to renewable energy must be accelerated, considering the country's potential, and at the same time, the continuity of this process must be maintained to achieve the targeted efficiency. On the other hand, it is also crucial to determine the type of fuel that will be used in thermal power plants and in what proportion. The main fossil fuels used are lignite, natural gas, coal and oil. When the emission intensity of natural gas is analyzed, it results in an emission intensity at or below half that of coal, oil, and especially lignite. Of course, while the prioritization of renewable energy sources is significant, natural gas can be the most appropriate choice among fossil fuels (Sahin & Esen, 2022).

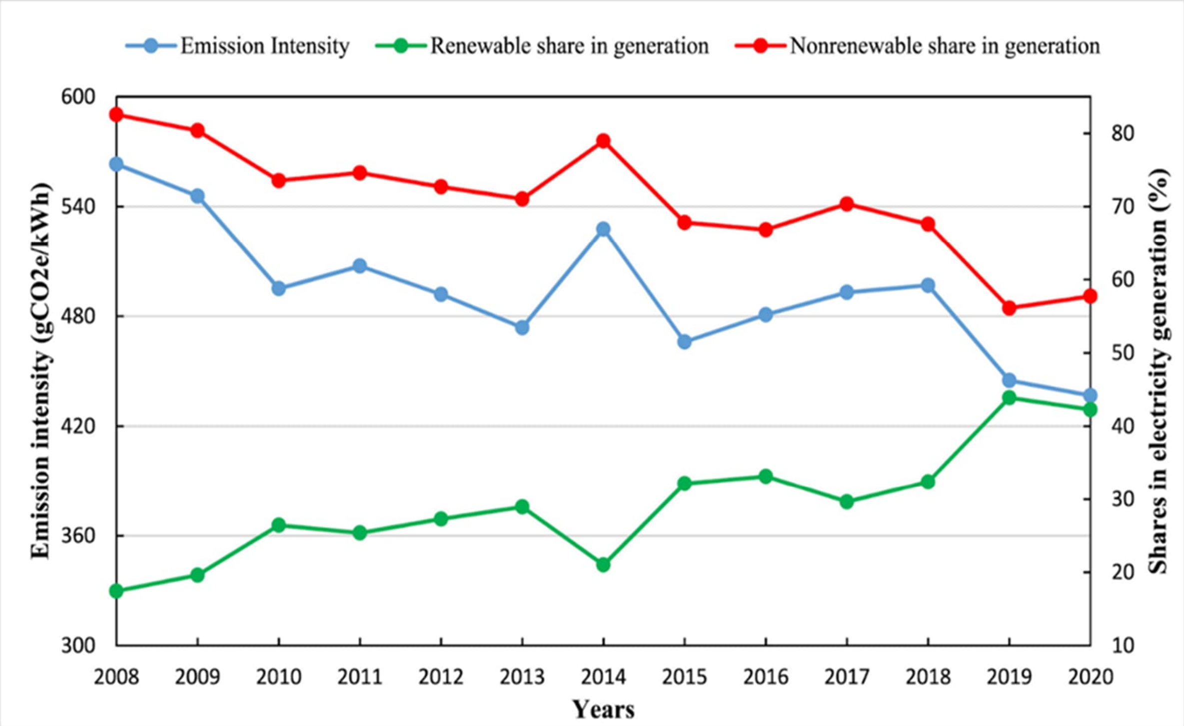

Figure 2.6. Renewable and non-renewable share in electricity generation (%) and emission intensity (gCO_2e/kWh) between 2008-2020

Even though both studies include and refer to economic factors as a result, the other study appears to focus more on the financial aspect (Ari, 2023). The study's two main objectives were to explore the driving factors behind emissions in the electricity sector and to examine emission reduction through a comparison of BaU and low-carbon policies. Similarly, the potential for Turkey's transition to renewable energy (including solar, wind and hydropower) was demonstrated in this study. Increasing the utilization and installed capacity of solar and wind energy, particularly renewable energy sources, is crucial for reducing Turkey's current account deficit and ensuring energy supply security. For this purpose, the electricity infrastructure needs to be strengthened, that is, a robust transmission and distribution infrastructure system needs to be established (Ari, 2023). In addition to the renewable energy system, CCS technology especially must be proved for proper commercial and industrial use. In the long term, consideration for the integrating the CCS into thermal plants is significant while minimizing the use of inevitable fossil fuels (Ari, 2023; Plastics Europe, 2023).

In addition, from a different perspective, the implementation of renewable energy resources in various regions was examined from multiple angles using the EnergyPLAN model and the SWOT analysis methodology (Zaimoğlu & Pehlivanzade, 2023). One of the study areas is Turkey, and both methodologies provided insights into Turkey's transition to renewable energy from socio-economic, geopolitical, and environmental perspectives. The first methodology, EnergyPLAN, is a tool that analyzes energy systems based on hourly data input and output. This model can support regional and national energy policies and strategies. For this energy-related study, inputs were renewable energy sources, demands, costs, and installed plant capacities and outputs were energy balances, fuel utilization, total expense, imports/exports, and yearly productions. Looking at these inputs and outputs, renewable energy was discussed not only in environmental terms but also in other relevant aspects (Zaimoğlu & Pehlivanzade, 2023). The study also supported the idea and evidence that the country's economy can benefit from increased contributions when a scenario focused on solar and wind energy as renewable energy sources is implemented and their use is prioritized. In other words, three different scenarios were created in this study, and it was assumed that the utilization of solar and wind energy, the two renewable energy sources, increased by 5% from one scenario to the next. In line with these results, the economic contribution of wind and solar resources at the market level was presented numerically as 47% and 41%, respectively (Zaimoğlu & Pehlivanzade, 2023). Like the study conducted by Ari (2023), this study also corroborates the importance of increasing the use of wind and solar energy.

In the other methodology in the same study, namely, SWOT analysis, as the name suggests, the extent to which renewability is applicable was investigated through the features of strengths, weaknesses, opportunities, and threats. With SWOT analysis, it is possible to examine four different aspects of the path to decarbonization. While SWOT analysis can be applied to many fields of study, in this study, it was discussed in line with the following examples (Zaimoğlu & Pehlivanzade, 2023):

- Strengths: increase in qualified labor force, brand development strategy, and adoption of advanced technology
- Weaknesses: increase in qualified labor force, brand development strategy, and adoption of advanced technology
- Opportunities: emerging markets, the advent of technological improvements, and evolving customer perspective
- Threats: regulatory-related updates, troubles with economic issues, and intense competition.

Due to its geographical location, Turkey acts as a bridge between the Europe and the Middle East in terms of energy trade. In accordance with the policies published in Turkey, it aims to enhance energy security, ecological sustainability and economic development in a coordinated manner. With well-defined and proper policies, it also seeks to increase the share of renewable energy use. These goals are of strategic importance both nationally and internationally (Yılmaz, 2012). However, for Turkey, limited financial resources and dependence on traditional energy sources may pose challenges in the transition to renewable energy as well as cooperation with neighboring countries and fluctuations in the energy market. On the other hand, increasing the use of domestic renewable energy can provide intended results in terms of energy security and reduce dependence on imports (Zaimoğlu & Pehlivanzade, 2023).

In conclusion, these studies emphasize the importance of not only renewable energy but also energy efficiency. The main point drawn from all the studies is that the economic dimensions of the business should be taken into account when examining environmental impacts, considering the country's current economic situation. In particular, the high initial investment costs for renewable energy need to be addressed, as well as the requirements for robust infrastructure, training, and R&D studies. Overall, the transition to renewable energy is essential if optimum economic, social, technological and geographical conditions are met. When we look at Turkey, it is an important aspect that it can reduce foreign dependency on fossil fuels.

3. METHODOLOGY

This study was conducted using GaBi 9.2.1.68 software, based on two specific standards, ISO 14040 and ISO 14044, which outline the basic principles of Life Cycle Assessment. Firstly, the goal and scope of the study were defined. In this context, the information about the functional unit of the materials studied was provided, as well as my aims, and illustrated my system boundaries. Secondly, data was collected for the determined goal and scope. Data inventory is one of the challenging parts of the study. Within the context of this study, data were mainly compiled from national and international publications, literature articles and projection studies. Thirdly, the life cycle impact assessment was done by determining relevant midpoints (problem-oriented) and endpoints (damage-oriented). Fourthly, a sensitivity analysis was conducted to compare the impacts of reuse and recycling on PET and glass bottles. Lastly, the results were discussed within the scope of the impact assessments.

3.1. Goal and Scope

3.1.1. Goal

This study aims to conduct an LCA study within the scope of the ISO 14040 and ISO 14044 standards for three different packaging types (PET, glass and aluminum) and analyze how the measures mentioned in the following can change the environmentally detrimental effects of the products. According to the determined baseline scenario (2020), there was measured the importance of transitioning to decarbonization by implementing renewable electricity generation (increased renewable electricity generation share by source), electrification in the production processes (especially shifting from high thermal energy to electrification, according to the European targets, in the selected production steps) and increased recycled content; and also recycling, and reuse targets for 2035 and Turkey’s net-zero year (2053).

3.1.2. Scope and System Boundaries

From a quantitative perspective, extensive system boundaries were illustrated. For each beverage packaging type, the system boundary was started from pre-consumer stage (including raw material extraction and transportation, raw material and semi-product processing, targeted material production) to post-consumer stages (reuse, recycling, recovery, and landfill). Turkey was selected as the geographic scope for the share of renewable electricity generation by source.

The functional unit for this study is 1 million beverage packaging bottles (for PET and glass) and cans (for aluminum) for each packaging type. PET, glass and aluminum packaging products of the selected brand sold in grocery stores were used as reference materials. The study was conducted by weighing the empty bottles and cans of the products sold on the market. Furthermore, the products were weighed using a digital scale with a precision of 0.1 grams. The purpose of this exercise is to take one unit of a real product and adapt it to the relevant processes of the product. Since this is a product and material approach study, the PET bottle's HDPE cap, LDPE label, and auxiliary material were removed. For the glass bottle, the adhesive paper label was removed, and the metal crown was removed. However, this was not the aluminum case; even though different alloys were used for the cap and body, the total mass of the aluminum bottle was assumed to be completely the same alloy (the alloy used for the body of an aluminum can).

To ensure the accuracy of the weighing process, the products were allowed to dry, and this process was repeated three times for each product. The results of this weighing (by multiplying with the functional unit) are attached to this study as given in Table 3.1 below. The unit product volumes for PET, glass, and aluminum are 450, 300, and 330 ml, and the individual masses of each product are 22.5 g, 298.2 g, and 13.2 g, respectively.

Table 3.1. Product mass results for the functional unit

Packaging type	ml	1 million bottles (tons)
PET Bottle	450	22.5
Glass Bottle	300	298.2
Aluminum Can	330	13.2

Electricity-related measures for decarbonizing production processes were also defined for each packaging material. In line with measures to achieve decarbonization targets, the electrification of thermal processes and policy improvements can be implemented to achieve these goals. For each packaging material type, EU publications were taken into account to refer to it. Information about these measures was retrieved from the reports published by Plastics Europe, FEVE, and the European Commission. According to these reports, the following energy-related measures were taken into account:

a) PET: For both 2035 and 2053, electrification in steam cracking (Plastics Europe, 2023),

b) Glass: For 2035, hybrid-based melting furnaces (80% replacing electricity) and for 2053, fully electricity-based melting furnaces (FEVE, 2024),

c) Aluminum: For both 2035 and 2053, shifting to the electrification of the Bayer process (Zore, 2024).

All scenarios defined within the scope of the study and references used for determining them are listed in detail in Table 3.2 and Table 3.3. While scenarios S1-S5, in Table 3.2, are target-based, scenarios in Table 3.3, S6 and S7, are not. For S6 and S7, a sensitivity analysis was conducted to understand individual impacts of reuse and recycling of PET and glass bottles. Additionally, the assumptions considered for each scenario are listed in Table 3.4 below.

Table 3.2. Scenario numbers and definitions of the scenarios

Scenario	**Definition**	**References**
S1:	It covers the production of 1 million (functional unit) PET, glass and aluminum packaging products in 2020. According to this scenario, electricity production values in 2020 (published by MENR) were used. To observe the differences, electrification was not applied in the selected processes of the products, and recycled content was not utilized. Additionally, post-consumer stages were not assessed within the scope of this scenario.	(Ministry of Energy and Natural Resources, 2022)
S2:	It covers the production of 1 million (functional unit) PET, glass and aluminum packaging products in 2035. According to this scenario, the projected electricity production data for 2035 was used. The use of recycled content was included. In PET, glass and aluminum, 47.5%, 55% and 60% of the materials, respectively, consist of recycled content. The transition to full electrification in steam cracking for PET and the Bayer process for aluminum, as well as to a hybrid-based melting furnace for glass, was applied.	(European Commission, 2022; European Union, 2025; FEVE, 2024; Plastics Europe, 2023; Ragonnaud, 2024; Renewable Carbon News, 2025; SHURA, 2023; Zore, 2024)
S3:	It covers the production of 1 million (functional unit) PET, glass and aluminum packaging products in 2053. According to this scenario, the projected electricity production data for 2053 was used. The use of recycled content was included. In PET, glass and aluminum, 65%, 70% and 80% of the materials, respectively, consist of recycled content. Full electrification was implemented in steam cracking for PET, in the glass melting furnace and in the Bayer process for aluminum.	
S4:	This scenario applies to the post-production stages of 1 million (functional unit) PET, glass and aluminum in 2035. According to this scenario, projected electricity generation data for 2035 was used. In accordance with the EU targets for the post-consumer stages; 55% direct recycling, 25% reuse and subsequent recycling, 10% open-loop recycling, 5% incineration and 5% landfilling for PET; 32.5% direct recycling, 57.5% reuse and subsequent recycling, and 10% landfilling for glass; and finally, 90% recycling, 5% incineration and 5% landfilling for aluminum were determined.	(European Aluminium & Metal Packaging Europe, 2024; European Commission, 2022; European Commission (Access date: 01/04/2025), n.d.; European Union, 2025; Ferrara et al., 2021; FEVE, 2024; Plastics Europe, 2023; Ragonnaud, 2024; Renewable Carbon News, 2025; SHURA, 2023; Zore, 2024)
S5:	This scenario applies to the post-production stages of 1 million (functional unit) PET, glass and aluminum in 2053. According to this scenario, projected electricity production data for 2053 was used. In accordance with the EU targets for the post-consumer stages; 50% direct recycling, 40% reuse and subsequent recycling, 5% open-loop recycling and 5% incineration for PET; 10% direct recycling, 85% reuse and subsequent recycling, and 5% landfilling for glass; and finally, 100% recycling for aluminum were determined.	

Table 3.3. Sensitivity Analysis Scenarios

Scenario	Definition	References
S6:	To understand the distinctive impacts of reuse and recycling processes for PET and glass products in 2035, a manual sensitivity analysis was conducted using the GaBi software. Unlike S4, products were not portioned for reuse and recycling, and the same input (1 million products) was applied in each process. According to this scenario, the projected electricity production data for 2035 was used.	(SHURA, 2023)
S7:	To understand the distinctive impacts of reuse and recycling processes for PET and glass products in 2053, a manual sensitivity analysis was conducted using the GaBi software. Unlike S5, products were not portioned for reuse and recycling, and the same input (1 million products) was applied in each process. According to this scenario, the projected electricity production data for 2053 was used.	(SHURA, 2023)

Table 3.4. Key assumptions and their relevant scenarios

	Relevant Scenario	References
Turkey Electricity Generation by Source:		
In the electricity generation shares for 2035 and 2053, CCS was not included and for wind generation, onshore and offshore systems were not considered separately.	All scenarios	
According to the MENR, the thermal energy data that was provided as a single data point was approximately allocated between hard coal (70%) and natural (30%), based on the MENR's 2024 electricity generation data.	All scenarios	(Ministry of Energy and Natural Resources (Access date: 06/04/2025), n.d.)
Energy Source Selection (Geographic):		
As the database setting, thermal energy, steam and electricity resources were selected according to Germany (DE) as a single country or EU-28.	All scenarios	
PET Bottle Production:		
For transportation of raw material, no material loss was assumed.	S1, S2 and S3	
No waste emission was numerically provided; this issue was adjusted according to this comparative study (except for salt removal).	S1, S2 and S3	
For 2035 and 2053, the cooling water in steam cracking decreased by 60% compared to thermal energy used in 2020.	S2 and S3	(Tiggeloven et al., 2023)
PET Post-consumer Stage:		
The landfill and incineration data were provided based on the GaBi dataset.	S6 and S7	
As a waste output, wastewater data was provided only for the washing process.	S4, S5, S6 and S7	
Glass Bottle Production:		
For transportation of raw materials, no material loss was assumed.	S1, S2 and S3	
The amount of cooling water was calculated according to the provided reference. Additionally, the reference stated that the cooling water used in the electricity is 20% of the cooling water used in the thermal energy.	S1, S2 and S3	
As a waste output, only the CO_2 emission that was produced because of the raw material melting (limestone and soda inputs) was provided.	S1 and S2	(Uthayakumar, 2020; Westbroek et al., 2021)
Glass Bottle Post-consumer Stage:		
The landfill data was provided based on the GaBi dataset.	S4 and S5	
As a waste output, wastewater data was provided only for the washing process.	S4, S5, S6 and S7	
The amount of cooling water was calculated according to the provided reference. Additionally, the reference stated that the cooling water used in the electricity is 20% of the cooling water used in the thermal energy.	S4, S5, S6 and S7	(Uthayakumar, 2020)
Aluminum Can Production:		
For transportation of raw material, no material loss was assumed.	S1, S2 and S3	
As implemented in the steam cracking process (in PET Bottle Production), for 2035 and 2053, the cooling water in the Bayer Process decreased by 60%, compared to thermal energy used in 2020.	S2 and S3	(Tiggeloven et al., 2023)
As a waste output, the red mud was considered to be generated in the alumina production.	S1, S2 and S3	
Aluminum Can Post-consumer Stage:		
No waste emission was numerically provided	S4, S5, S6 and S7	
For the incineration and landfilling stages, it was not able to be reached explicitly to aluminum data, so the aluminum incineration and landfill data were considered as municipal waste (data was provided from the GaBi dataset).	S4 and S5	

3.2.2.1. System Boundaries. For each material, the pre-consumer and post-consumer stages are illustrated in Figures 3.1, 3.2, and 3.3. While the pre-consumer stage encompasses the steps from raw material extraction to material production, the post-consumer stage includes reuse (for PET and glass only), recycling, incineration (except for glass) and landfilling. PET recycling system boundaries were redrawn based on the literature (Chairat & Gheewala, 2023).

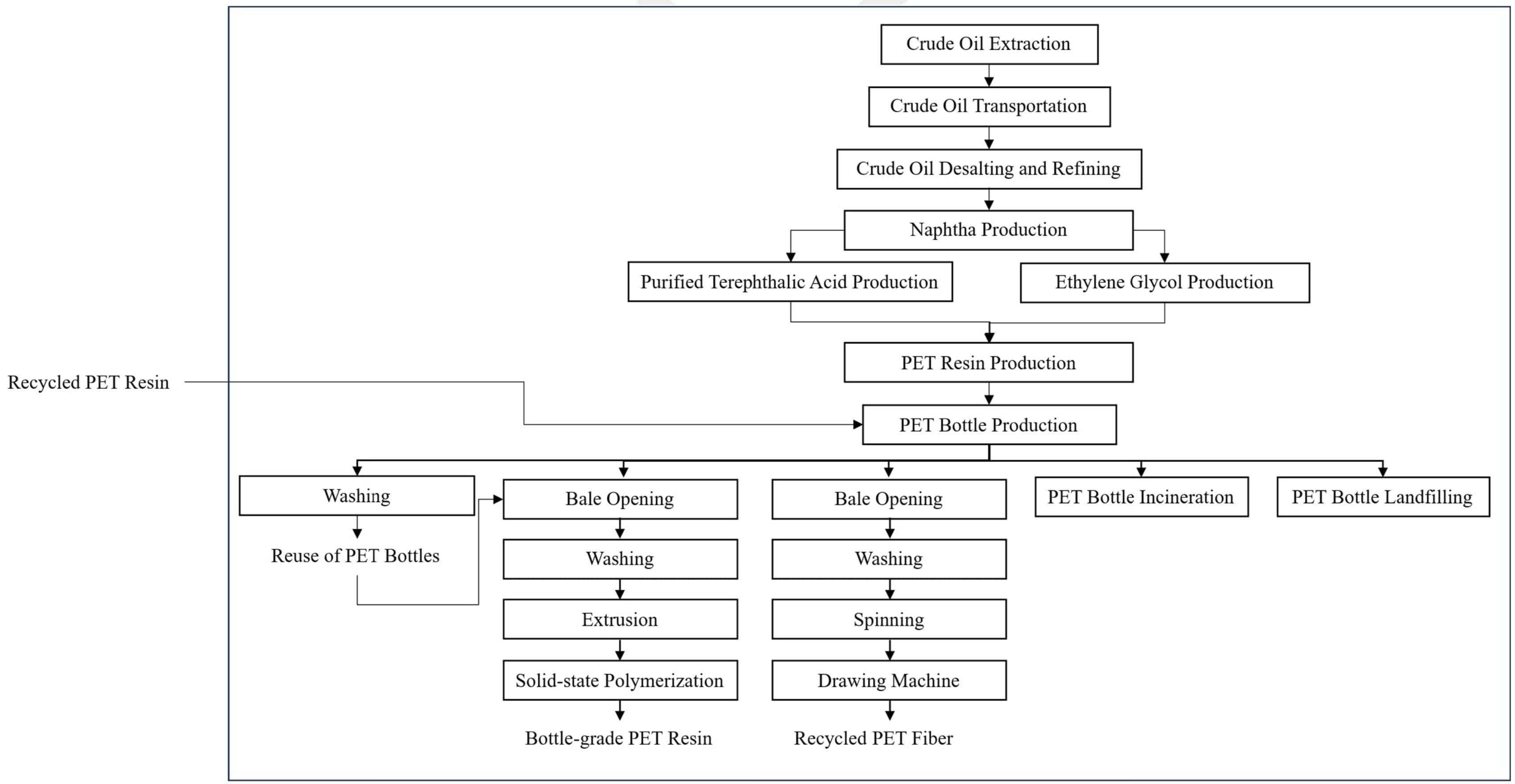

Figure 3.1. System boundary of the PET bottle

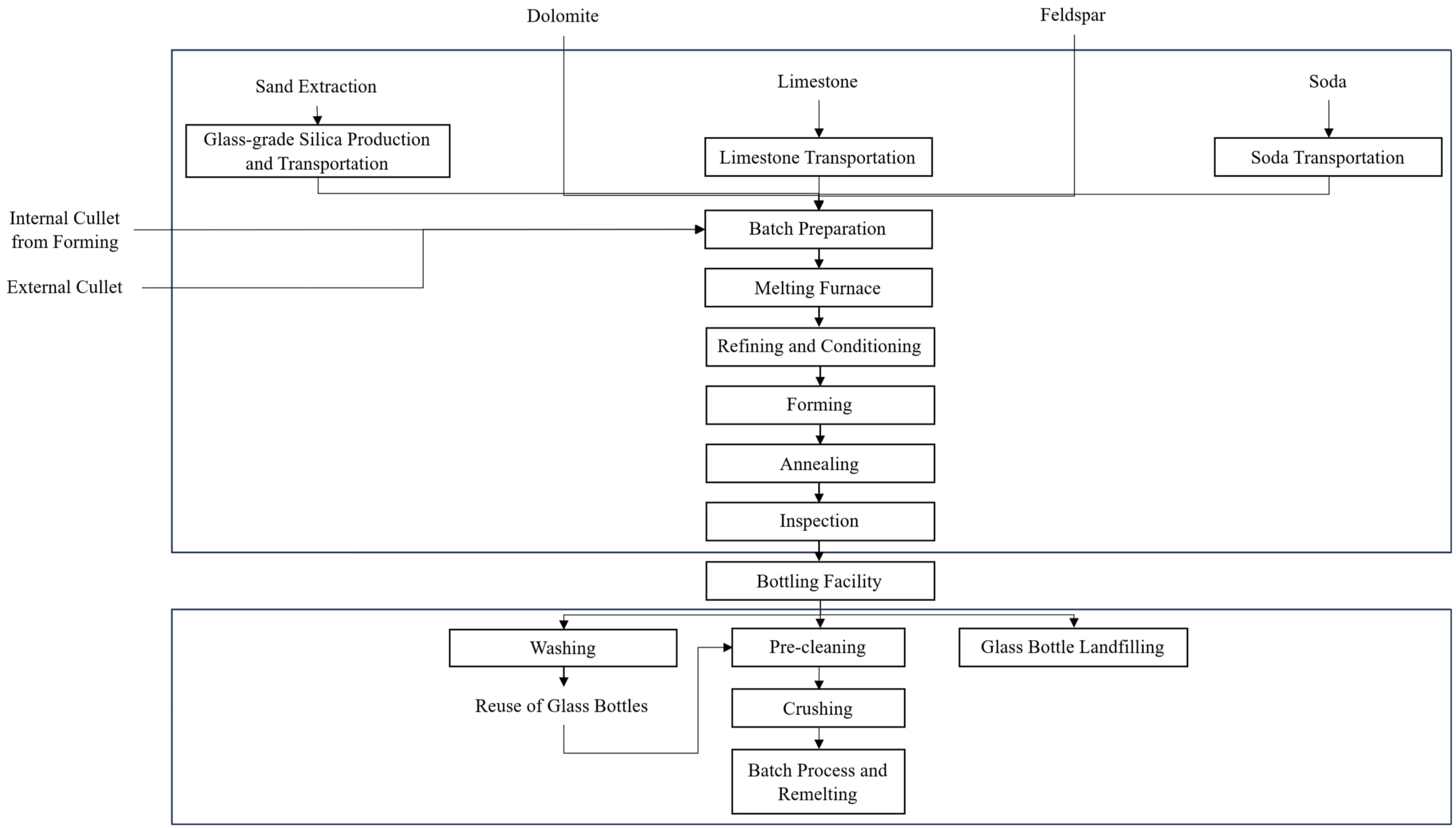

Figure 3.2. System boundary of the glass bottle

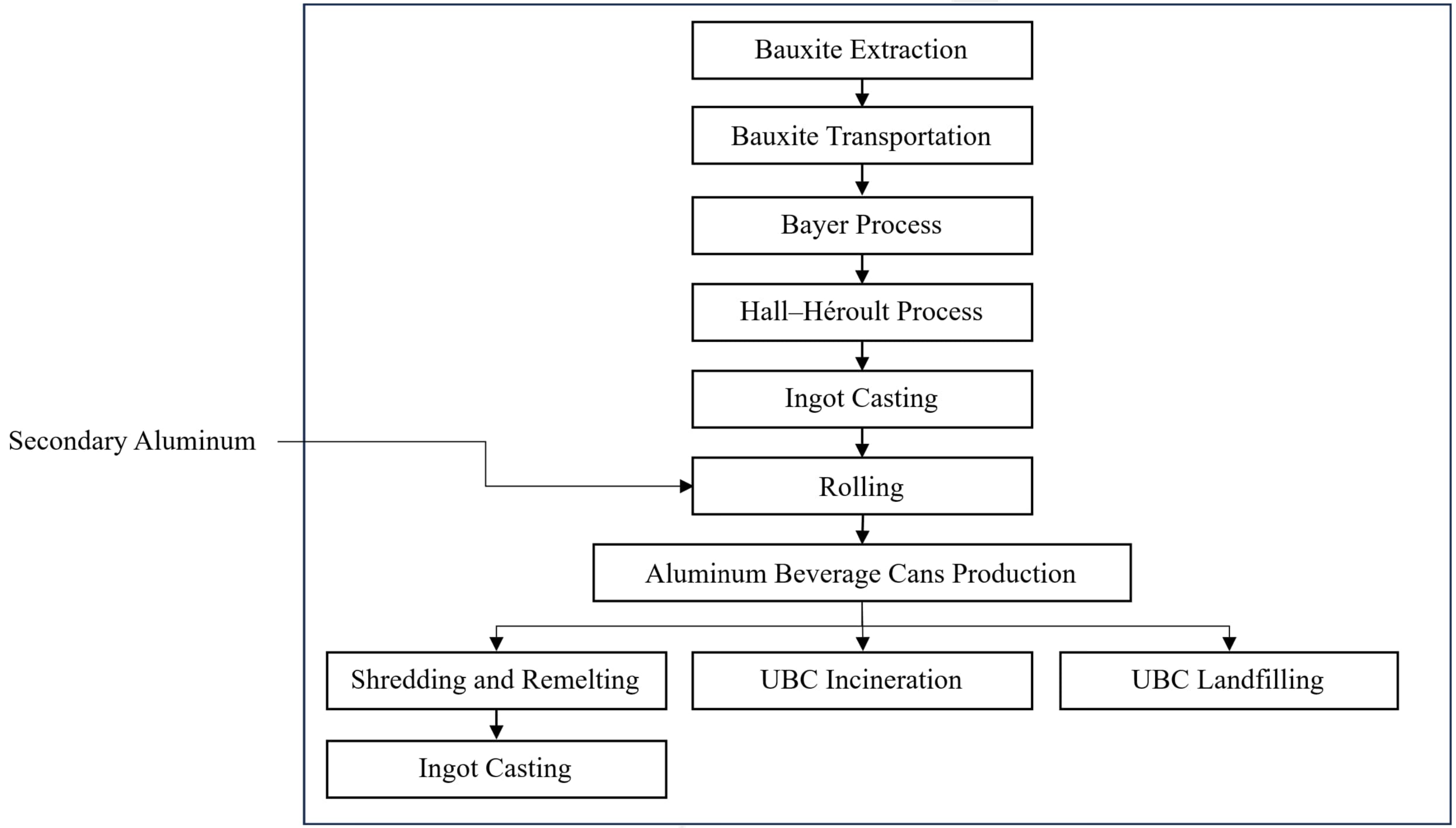

Figure 3.3. System boundary of the aluminum can

3.2. Life Cycle Inventory Analysis and Key Assumptions

For material and product processing, national and international publications, literature-based articles, books and official websites were utilized for mass and energy data. In this study, transportation data was only considered for primary raw material transportation. The transportation data varied according to the types of packaging materials. Specifically, and respectively; crude oil transportation data were collected from BOTAŞ; transportation data of the primary raw materials for glass production (only sand, limestone and soda transportation data were included in the system boundary); and bauxite transportation data were determined according to the GaBi (Ecoinvent) dataset. Database settings for crude oil transportation were provided in the GaBi software but the local setting was arranged based on BOTAŞ data (BOTAŞ (Access date: 08/01/2025), n.d.). For bauxite and glass raw materials, no data arrangement was performed, and the dataset was used entirely as provided by the GaBi software.

Specific to this study, relevant data are presented in Figure 3.4 (European Aluminium & Metal Packaging Europe, 2024; European Commission, 2022; European Commission (Access date: 01/04/2025), n.d.; European Union, 2025; Ferrara et al., 2021; FEVE, 2024; Ministry of Energy and Natural Resources, 2022; Ragonnaud, 2024; Renewable Carbon News, 2025; SHURA, 2023). For the 2020 Baseline Scenario, data is not presented in Figure 3.4 (b) and (c), because this scenario included only the pre-consumer stage and zero recycled content.

Both local and international regulations and targets covering beverage packaging are in place. Relevant local regulations for packaging materials include Packaging Waste Control Regulation (O.G. No. 31523, 26/06/2021), Zero Waste Regulation (O.G. No. 30829, 12/07/2019), Waste Management Regulation (O.G. No. 29314, 02/04/2015), GEKAP (O.G. No. 30995, 31/12/2019). From an international perspective, Packaging and Packaging Waste Regulation 2025/40 (PPWR), CEAP (Circular Economy Action Plan), Paris Agreement, and the EU Green Deal are the relevant frameworks concerning the packaging materials. When comparing Packaging Waste Control Regulation and PPWR, the former mainly focuses on post-consumer stage, whereas the latter addresses on both the pre-consumer and post-consumer stages. Consequently, PPWR is more comprehensive than Packaging Waste Control Regulation.

In PPWR, not all exact targets were published for 2035 and the net-zero target year. Therefore, some data were interpolated in accordance with the PPWR regulations, and some were inferred based on EU publications. For material-specific data inferences, European publications and literature-based articles were utilized. Moreover, the determined recycled content values in accordance with the PPWR are for single-use materials. Nevertheless, within the scope of this study, the environmental effects were compared and only one cycle of reuse and recycling was considered.

According to the National Plan, the Ministry of Energy and Natural Resources (MENR) published its forecast for renewable energy use in relation to the net-zero targets (Ministry of Energy and Natural Resources, 2022). However, there is no distribution-based data on net-zero targets. Thus, one can reach out to the SHURA (Energy Transition Center) for its “Net Zero 2053: A Roadmap for the Turkish Electricity Sector” publication. This comprehensive study was reviewed for the renewability of electricity generation. SHURA was founded by ECF, Agora Energiewende and IPC at Sabancı University. SHURA adopts novel approaches to make contributions to decarbonization in renewable energy and energy efficiency. Their prominent features are utilizing the most available and best data and making realistic analyses for the future. Additionally, while doing this, they take into account the perspectives and views of many stakeholders. These results contribute to a deeper understanding of financial potential, technical feasibility, and relevant policies associated with this transition (SHURA, 2023).

In addition to the MENR’s 2020 electricity generation distribution data, the study also includes data for 2035 and 2053 on renewability in electricity consumption in Turkey. For 2020, the MENR’s reported data was used, while for 2035 and 2053, SHURA’s report was used. The reason why I took SHURA’s report as a reference is that, by using the actual data of Turkey (published by the MENR) in 2020, they provided the projection of renewable electricity generation for the future years in the form of 5-year periods through the methodology and modeling, which is widely used in Europe, namely CompactPRIMES (SHURA, 2023). In addition to this reason, as evidenced by the projection of SHURA's study, it can be demonstrated that the EU places a dominant emphasis on wind and solar energy as a result of the projection studies conducted (Busch et al., 2023; Rosslowe & Petrovich, 2025). The renewable electricity shares are shown in Figure 3.4 (a).

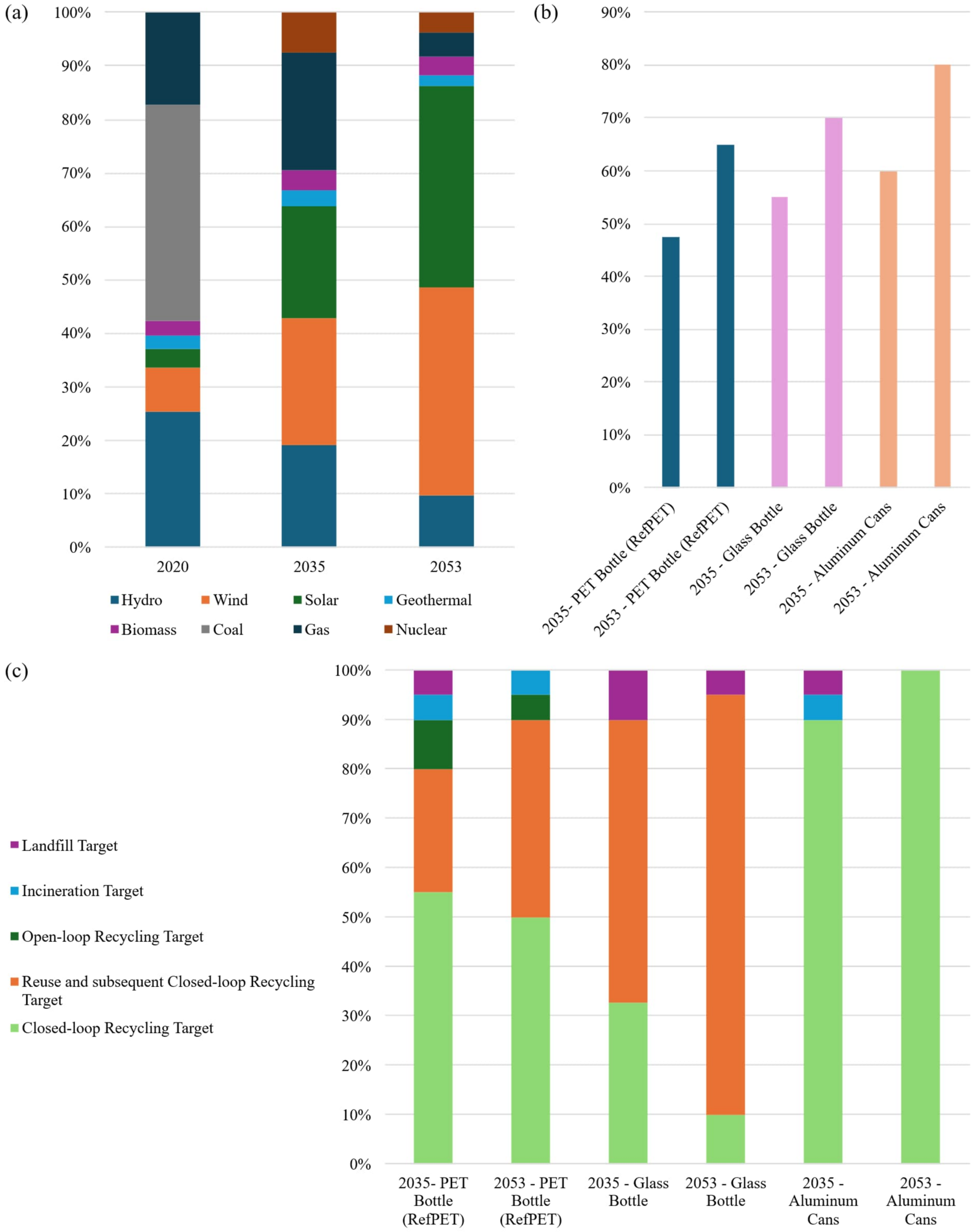

Figure 3.4. (a) Determined electricity generation distribution by source, (b) determined recycled content targets and (c) determined post-consumer scenario

For the relevant data (other than ready data on GaBi) of this study are presented in Table 3.5 below.

Table 3.5. Data References for the study

Process	References
PET Production	(Association of Plastic Recyclers, 2024; Barthe et al., 2015; BOTAŞ (Access date: 08/01/2025), n.d.; Devlet Planlama Teşkilatı, 2008; Dursch et al., 2009; Everly et al., 2017; Fetter Pruneda et al., 2005; Franklin Associates, 2020; Green et al., 2019; Kırşen Doğan, 2008; Meili et al., 2024; Perry et al., 1999; Sheehan et al., 1998; Tamoor et al., 2022; Tiggeloven et al., 2023)
Glass Production	(Atılgan Türkmen, 2020; Grbeš, 2016; Ministry of EUC and Dokuz Eylül University, 2019; Uthayakumar, 2020; Westbroek et al., 2021)
Aluminum Production	(Balomenos et al., 2011; European Aluminium, 2018; PE Americas, 2010)
PET Reuse	(Polyretec (Access date: 11/03/2025), n.d.)
PET Recycling	(Chairat & Gheewala, 2023; Kang et al., 2017)
Glass Reuse/Washing	(Tua et al., 2020)
Glass Recycling	(JXSC (Access date: 24/04/2025), n.d.; Uthayakumar, 2020)
Aluminum Recycling	(European Aluminium, 2018; PE Americas, 2010)

As well as the system boundaries of the study, the mass and energy flows were illustrated and presented below. Figures 3.5, 3.6, and 3.7 show the flow differences in PET, glass, and aluminum production by year, respectively. In 2035 and 2053, there occurred the transition to electrification in the ethylene production (in PET production), melting furnace (in glass production but glass melting furnace in 2035 is hybrid-based) and Bayer (in aluminum production) processes. On the other hand, when looking at the raw material inputs during the production stage, product inputs for PET and aluminum were provided as secondary data. For glass, secondary data was provided only for the sand beneficiation process (glass-grade silica production). For limestone and soda, which are the other raw material inputs for glass, the ready dataset in GaBi was used, and no raw material tracking was performed for dolomite and feldspar. Finally, Figures 3.8, 3.9, and 3.10 provide mass flow information for the post-consumer stages of PET, glass, and aluminum, respectively. It is also clear from Figures 3.8 and 3.9 that the post-consumer scenarios of PET and glass products are different from that of aluminum. According to S4 and S5, a portion of the PET and glass products was sent directly to recycling, while some were subjected to reuse and subsequent recycling processes. The reuse process was not practiced for aluminum.

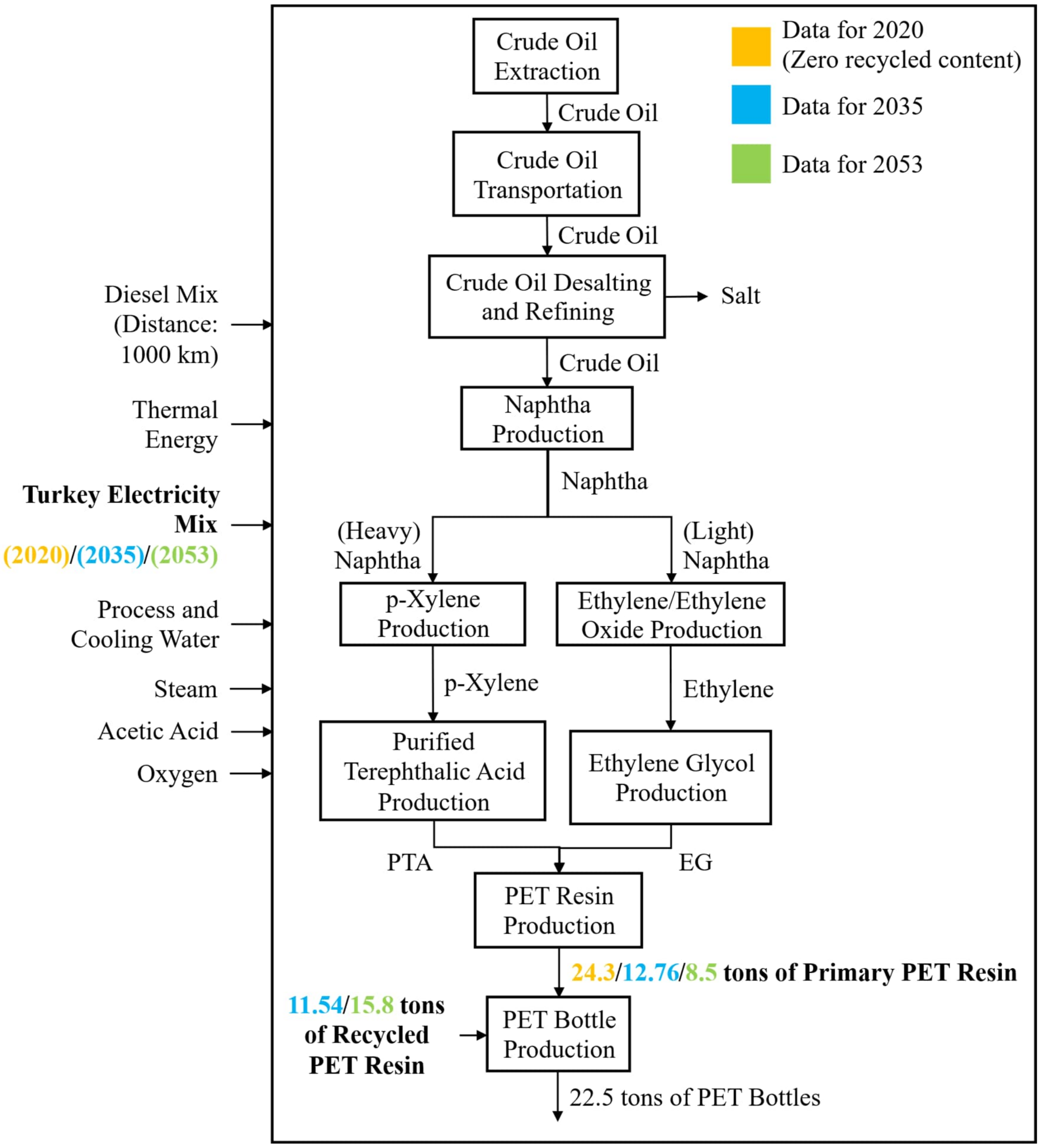

Figure 3.5. Mass and energy flowchart of the PET bottle production in 2020, 2035 and 2053

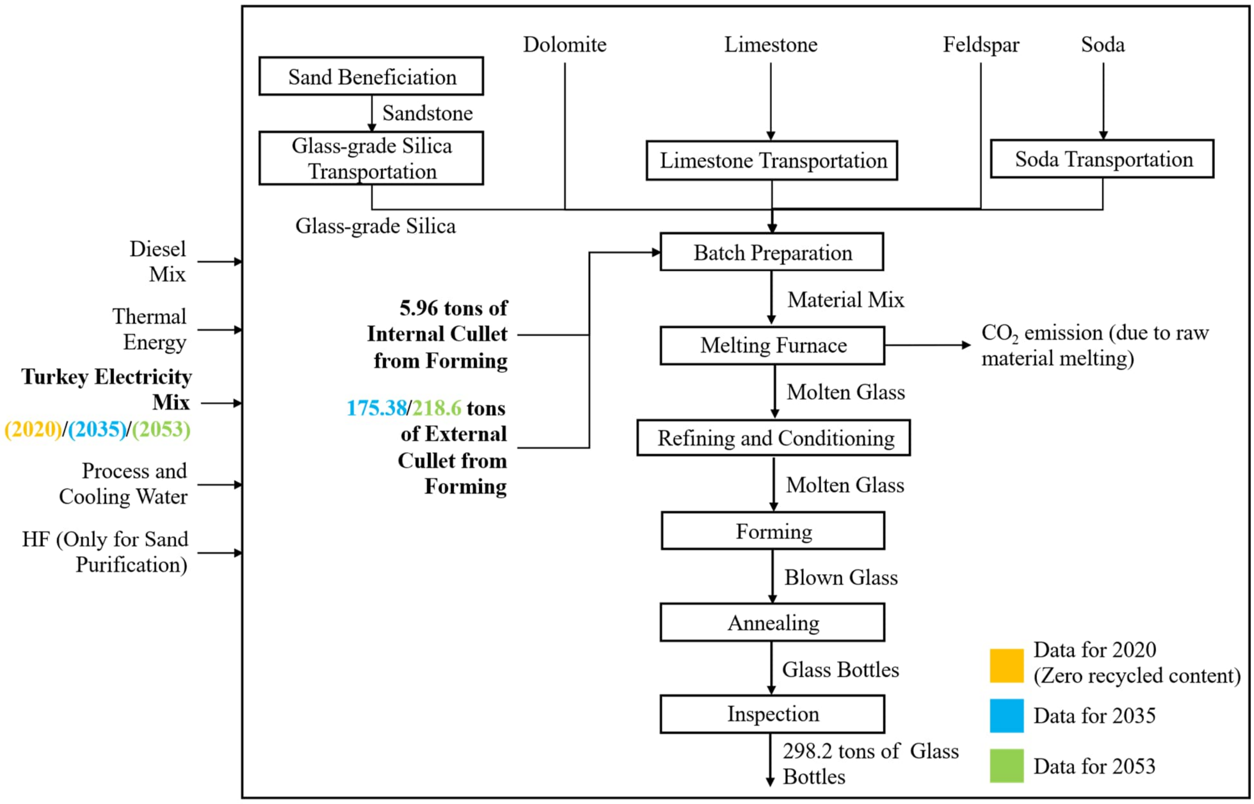

Figure 3.6. Mass and energy flowchart of the glass bottle production in 2020, 2035 and 2053

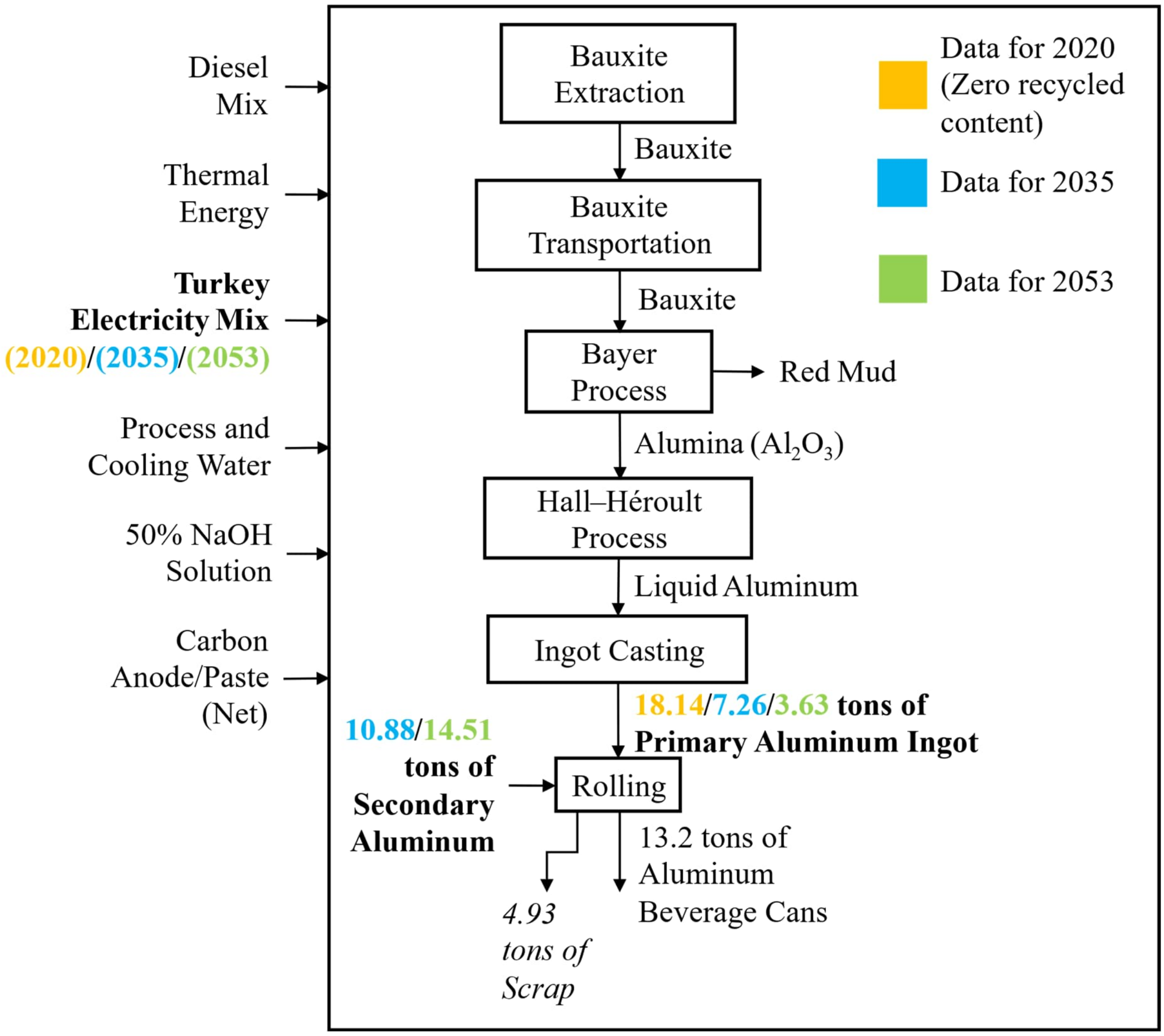

Figure 3.7. Mass and energy flowchart of the aluminum can production in 2020, 2035 and 2053

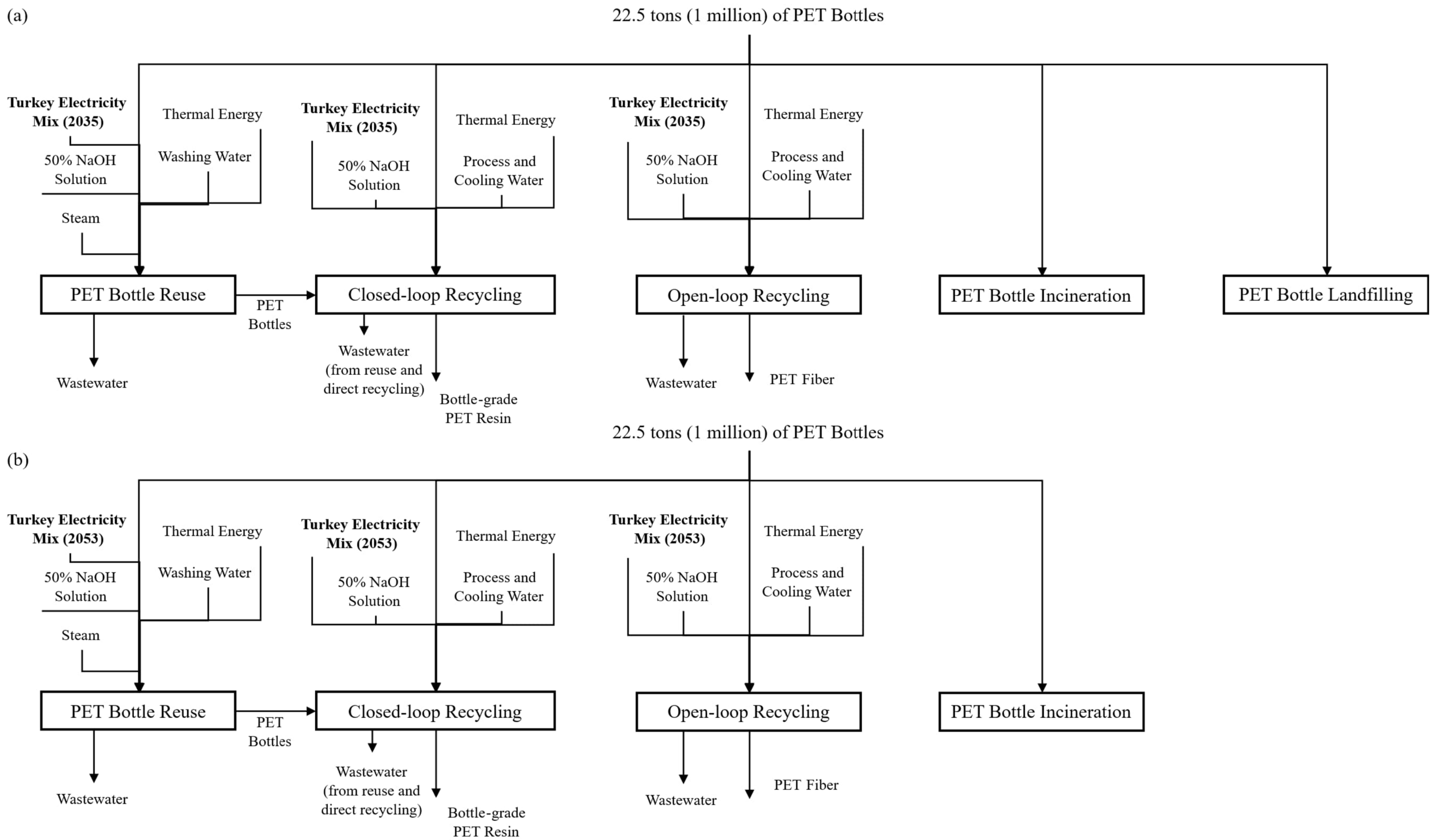

Figure 3.8. Mass and energy flowchart of the PET bottle (post-consumer scenario) (a) in 2035 and (b) in 2053

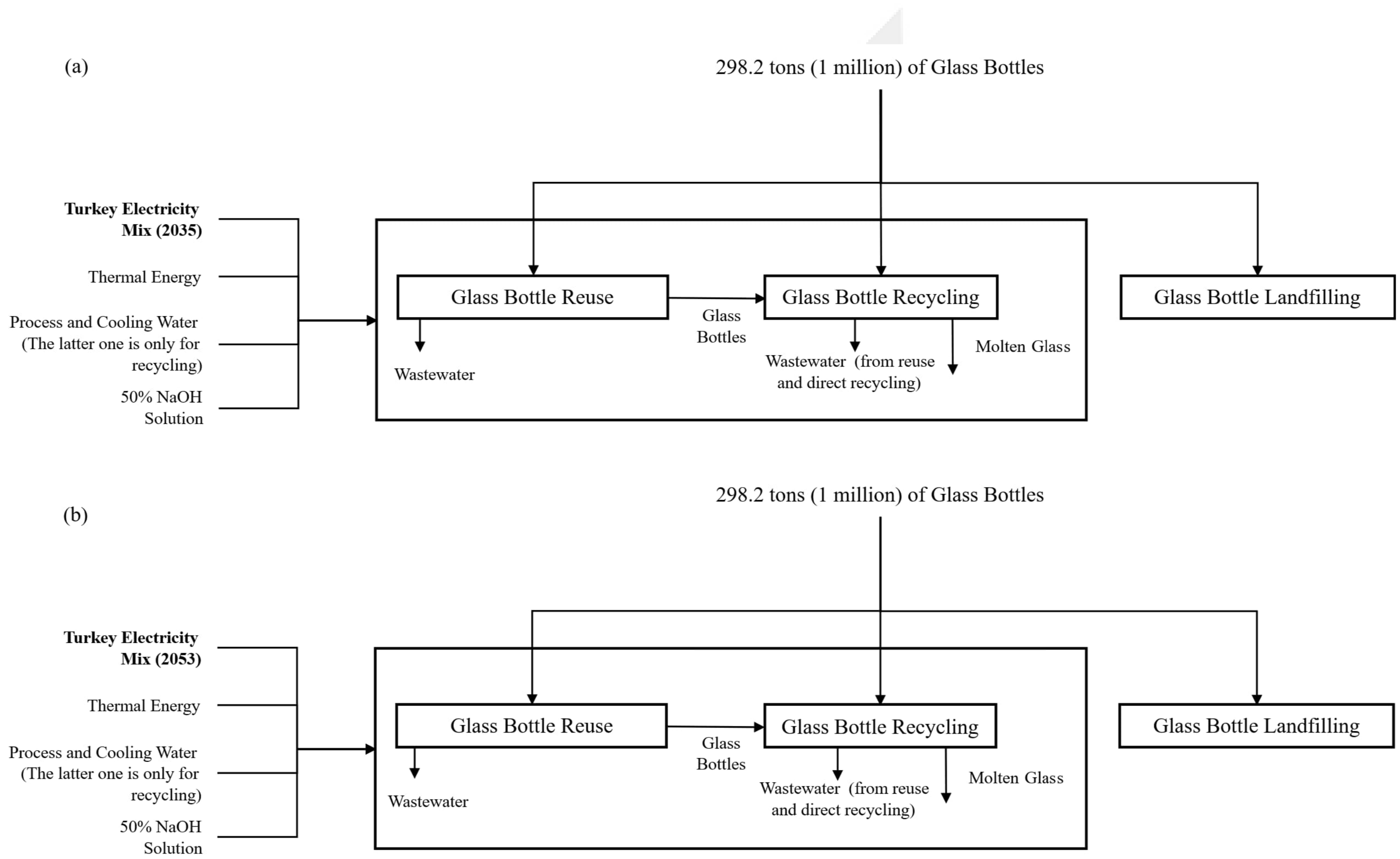

Figure 3.9. Mass and energy flowchart of the glass bottle (post-consumer scenario) (a) in 2035 and (b) in 2053

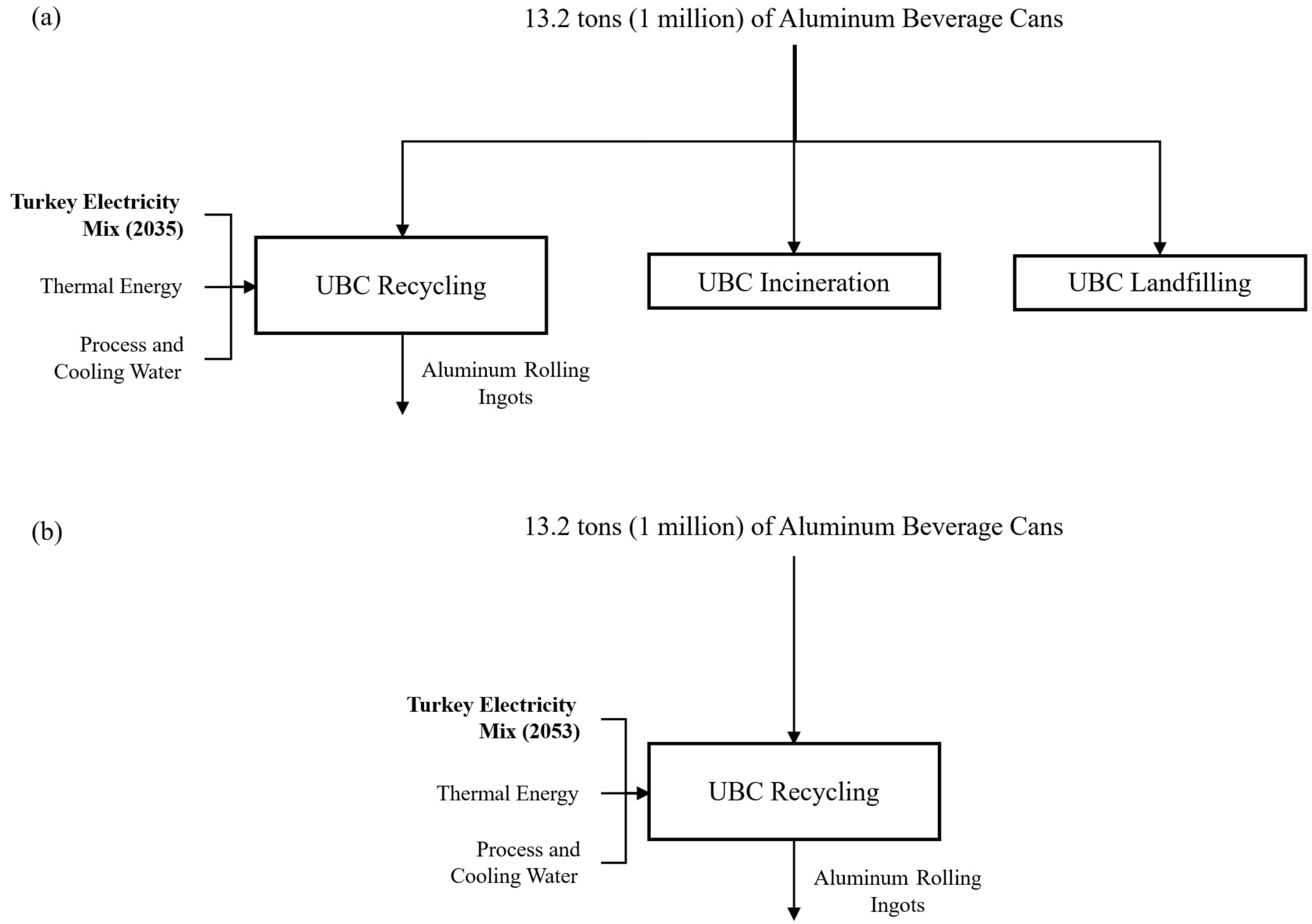

Figure 3.10. Mass and energy flowchart of the aluminum can (post-consumer scenario) (a) in 2035 and (b) in 2053

4. RESULTS

4.1. Life Cycle Impact Assessment

For the Life Cycle Impact Assessment, the ReCiPe 2016 v1.1 (Hierarchist) method was selected to provide more comprehensive results, including midpoint and endpoint impact categories. Thanks to the ReCiPe method, unlike some other methods - especially CML - it is not only limited to the midpoint impact categories but also enables analysis at the endpoint level. Endpoint impact categories can provide meaningful insights results not only for technical analysis but also for academic and decision-making processes. In summary, the ReCiPe method is a preferable method for benchmarking, developing policy recommendations or making strategic decisions.

4.1.1. Classification

At this stage, impact categories were selected depending on the literature and products. In line with the study's scope, the six selected impact categories are listed in Table 4.1 below and available midpoint conversion factors are presented (Huijbregts et al., 2016; Huijbregts, 2017; Toscano et al., 2019). The Climate Change category has been widely studied. The impact category of Fossil Depletion needs to be notably examined in the context of energy use in the raw material use and production phase (transition to electrification in steam cracking) for PET, as well as an impact category that needs to be calculated and interpreted for the transition from thermal energy to electrification in the production of glass and aluminum products. The Metal Depletion impact category provides information on raw material conservation, particularly in relation to the scenarios in the production of glass and aluminum products. By calculating the Freshwater Consumption impact category, the cooling water effect on the production of unconventional products and washing/pre-cleaning stages can be understood. Lastly, Photochemical Ozone Formation gives information about volatile organic compounds and Terrestrial Acidification is calculated to observe the impacts of energy and fuel consumption.

Table 4.1. Selected midpoint impact categories

Midpoint Impact Categories	Related Emissions/Descriptions	Midpoint Conversion Factors	
Climate change, incl. biogenic carbon [kg CO2 eq.]	CO_2 , CH_4 , N_2O, HFC, PFC	CO_2	1
		CH_4	34
		CH_4	36
		N_2O	298
Fossil Depletion [kg oil eq.]	Depletion of resources containing hydrocarbons and non-volatile materials (anthracite coal)	Crude oil (oil-eq/kg)	1
		Natural Gas (oil-eq/Nm^3)	0.84
		Hard Coal (oil-eq/kg)	0.42
		Brown Coal (oil-eq/kg)	0.22
		Peat (oil-eq/kg)	0.22
Freshwater Consumption [m^3]	Depletion of water for the use of process and cooling water	Industrial Surface Water	0.1
Metal Depletion [kg Cu eq.]	Decrease in ore grade	Relevant Chemical Element	Its MCF
Photochemical Ozone Formation, Ecosystems [kg NO_x eq.]	NO_x Non-methane volatile organic compounds (NMVOC)	NO_x	1
		NMVOC	0.29
Terrestrial Acidification [kg SO_2 eq.]	NO_x, NH_3 and SO_2	NO_x	0.36
		NH_3	1.96
		SO_2	1

4.1.2. Characterization

The magnitude of each selected impact category in the classification stage is measured, and each value obtained in this step has its corresponding unit (Cristobal-Garcia et al., 2016). In line with the selected impact categories for this study, ReCiPe 2016 v1.1, only the results of the midpoint impact categories were presented.

The results of the pre-consumer and post-consumer stages are presented in Figures 4.1 and 4.2, respectively, and their impacts were also discussed separately. At the same time, the post-consumer stages of PET and glass products were evaluated separately and aluminum was individually assessed.

4.1.2.1. Climate Change. When the scenarios for the pre-consumer stages are examined, decreases are observable in all S1, S2, and S3, depending on the years. In the Climate Change impact category, during the transition from S1 to S2, 60%, 61%, and 84% decreases took place for PET, glass, and aluminum, respectively; in the transition from S2 to S3, for the the same products, 41%, 35%, and 66% decreases were seen, respectively. In this process, the favorable environmental effects of increasing recycled content, transitioning to electrification in the selected processes, and increasing the share of renewable energy in electricity generation can be achieved. In addition, unlike the S1 scenario, the impact value of aluminum is the least in the S2 and S3 scenarios. This case can be explained similarly. The recycled content value for aluminum is higher in the S2 and S3 scenarios compared to other products. While the Hall-Héroult process is an electricity-intensive process in the production process of aluminum, the Bayer process has also been electrified, and electricity was used predominantly. Although recycled content and renewable electricity are also effective in reducing the environmental impacts of PET and glass products individually, the replacement of high thermal energy used in the steam cracking stage for PET and in the melting stage for glass with electrical systems reduces the impact in the Climate Change category. On the other hand, the results of S1 are consistent with the literature. Simon et al. (2016) demonstrated that the order of impacts for these selected packaging materials is glass, aluminum and PET. Additionally, considering the transition from S1 to S2 and S2 to S3, according to the studies performed by Chairat and Gheewala (2023) and Roosen et al. (2023), the outcomes showed that increasing recycled content reduces the GHG emissions. Similar to material-based comparison, the results support the energy-based studies quantitatively conducted by Sahin and Esen (2022) and Ari (2023). Their findings demonstrate that increasing the share of renewable energy reduces the emission intensity as g CO_2e/kWh.

In the S4 and S5 scenarios, PET and glass product impact categories decreased by 7% and 28%, respectively. Comparing PET and glass, PET has a lower impact than glass. In this process, the use of renewable energy in electricity, as well as the increasing reuse and recycling effect, reduced the Climate Change impact. Similarly, the impact value of aluminum decreased by 27%.

<u>4.1.2.2. Fossil Depletion.</u> In the S1, S2, and S3 scenarios, a similar decrease was observed depending on the year. When the transition from the S1 scenario to the S2 scenario was made, the decreased values for PET, glass, and aluminum are 52%, 43%, and 74%, respectively. From S2 to S3, these decreased values are 43%, 52%, and 67%, respectively. While PET has the lowest impact in the S1 scenario in the Fossil Depletion impact, aluminum is the least environmentally harmful in the S2 and S3 scenarios. Similar to the Climate Change impact results, the recycled content, electrification and electricity generation with high renewables decreases the environmental harms in the impact of Fossil Depletion.

From S4 to S5, outcomes revealed that the impact of PET reduced by 12%, and for glass, this value is 31%. Like the Climate Change impact, in the Fossil Depletion impact category, PET is more environmentally friendly than glass. Additionally, from S4 to S5, aluminum post-consumer value decreased by 3%.

<u>4.1.2.3. Freshwater Consumption.</u> For this impact category, outcomes are different from the previous two impact categories. In S1, S2, and S3 scenarios, PET has the highest impact, while aluminum has the least impact. From S1 to S2 and from S2 to S3, the impact of PET decreased by 46% and 31%, the impact of glass decreased by 42% and 29%, and the impact of aluminum reduced by 60% and 51%. One of the implications of this category is that increasing recycled content decreases Freshwater Consumption. Secondly, considering the transition from S2 to S3, shifting to the electrification process can reduce cooling water use in material production. On the other hand, even though shifting from thermal energy to electrification increases Freshwater Consumption, increasing renewables decreases Freshwater Consumption between these two scenarios.

When comparing the S4 and S5 scenarios, respectively, for the post-consumer stage, Freshwater Consumption increased by 3% for PET, by 12% for glass, and by 7% for aluminum. The impact order, from high to low, is glass, aluminum and PET.

4.1.2.4. Metal Depletion. This impact category is significant particularly for the examination of the production of glass and aluminum products in terms of raw materials. In this scenario, the impact on PET products decreased by 1% during the transition from S1 to S2, while it increased by 12% during the transition from S2 to S3. For glass and aluminum, it decreased by 53% and 15%, respectively, in the transition from S1 to S2 scenarios, while these values are 22% and 17%, respectively, in the transition from S2 to S3 scenarios. In S1, S2 and S3, the highest impact is in glass, followed by aluminum and PET, respectively. The main conclusion to be drawn from this is that in renewable electricity use, the metal depletion value increases as the share of renewables increases and as the transition from thermal energy to electrification is applied.

For the post-consumer stage, i.e., in S4 and S5 scenarios, the results for PET and glass increased by 5% and 38%, respectively, while for aluminum, the calculation result decreased by 20%. Furthermore, the environmental detriment of glass is much higher than that of PET.

4.1.2.5. Photochemical Ozone Formation. Similarly, in the Climate Change and Fossil Depletion impact categories, high reduction rates were observed in this impact category. When the transition from S1 to S2 is achieved, the reduction rates for PET, glass and aluminum are 60%, 53% and 84%, respectively, while in the transition from S2 to the S3 scenario, these reduction values are 35%, 32% and 53%, respectively. On the other hand, the lowest impact value from S1 belongs to PET, and for S2 and S3, aluminum achieved the lowest impact value. In short, similar inferences to those in the Climate Change and Fossil Depletion impact categories can be made for this impact category.

In the post-consumer stage, for both S4 and S5, all impact values dropped by 1%, 7%, and 11% for PET, glass, and aluminum, respectively. When comparing glass and PET products, which have similar post-consumer scenario trajectories, the impact of glass is much greater than PET.

4.1.2.6. Terrestrial Acidification. In each scenario (S1, S2, and S3), glass has the highest impact, followed by PET and aluminum. For PET, the transition from S1 to S2, and transition from S2 to S3, these results of this impact category decreased by 59% and 31%, for glass by 53% and 27% and for aluminum by 80% and 60%, recpectively. There is a significant decrease in this impact category when switching from thermal energy to electrified processes in the S2 and S3 scenarios and in contrast, a slight increase in this impact category was observed when switching from natural gas to electrified pocessess in the mentioned scenarios.

From S4 to S5, the impact results of PET and glass increased by 8% and 11%, and aluminum reduced by 5%. Similar to previous impact assessments, glass has a more significant impact than PET.

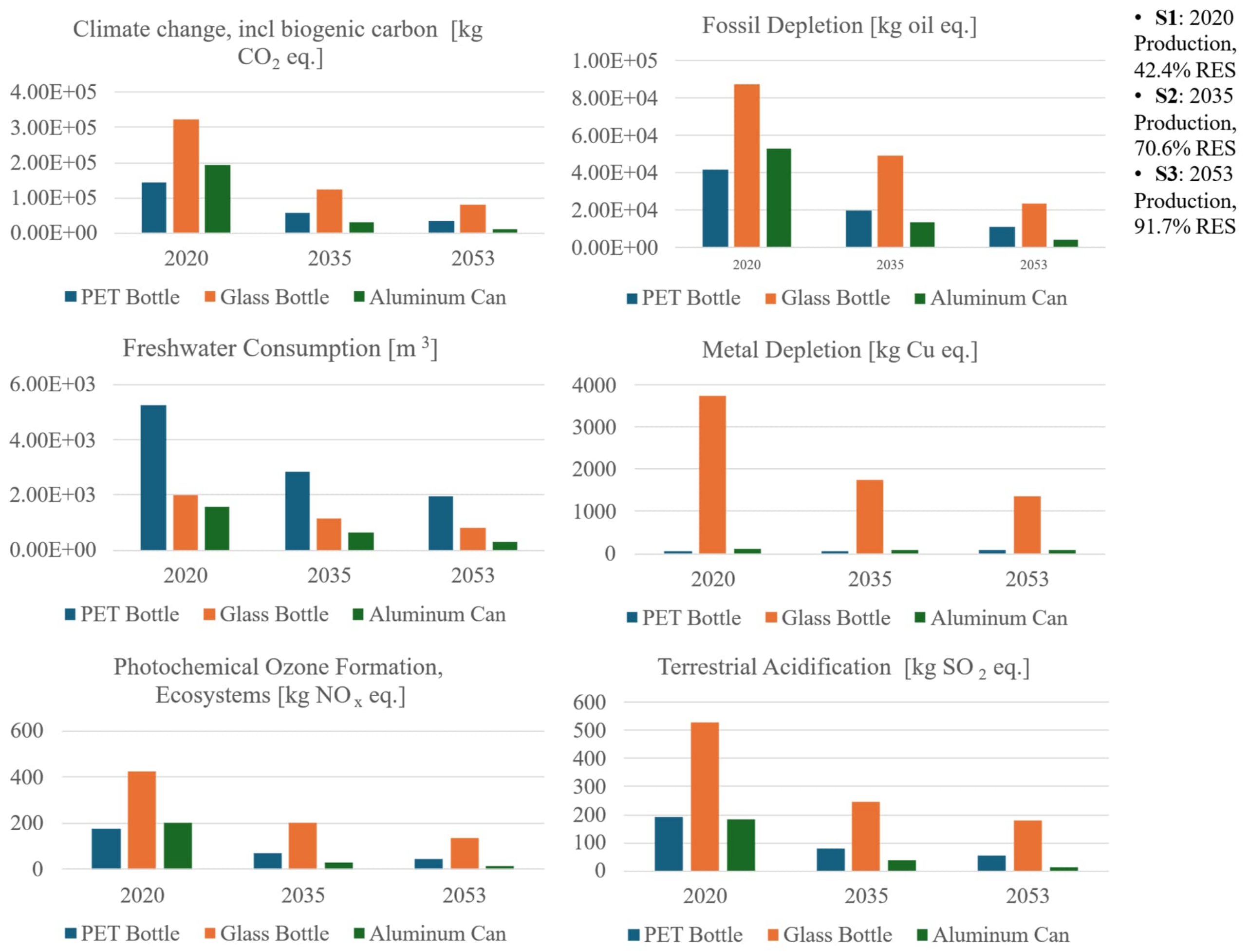

Figure 4.1. Characterization results of the pre-consumer stage

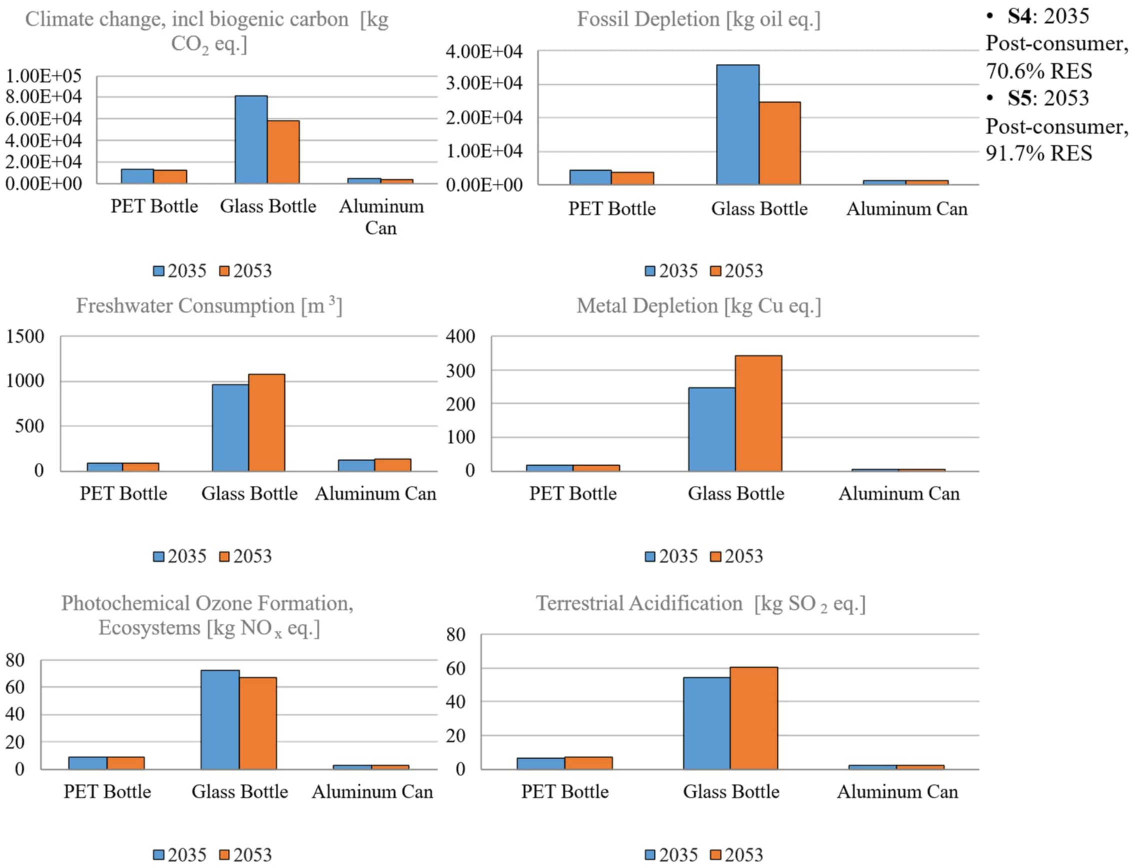

Figure 4.2. Characterization results of the post-consumer stage

4.1.3. Normalization

In this step, which follows the characterization, the results obtained from the impact assessment are multiplied by a certain value and these values are called normalization factors. As a result, the magnitude of the contributions to the impact categories can be calculated and compared relative to a reference unit, and thus, the results for this step are unitless (Cristobal-Garcia et al., 2016). Similar to the characterization step, only the midpoint impact categories were analyzed in this step.

Among the normalized values, shown in Figure 4.3, at the pre-consumer stage, Fossil Depletion has the highest impact share in S1, S2 and S3. However, it is not possible to reach such a singular implication for the second-highest impact category. For each scenario, followed by Fossil Depletion, the Freshwater Consumption impact category has the second-highest impact share for PET production. For glass and aluminum, Fossil Depletion is followed by Climate Change. On the other hand, Metal Depletion has the lowest share of all scenarios.

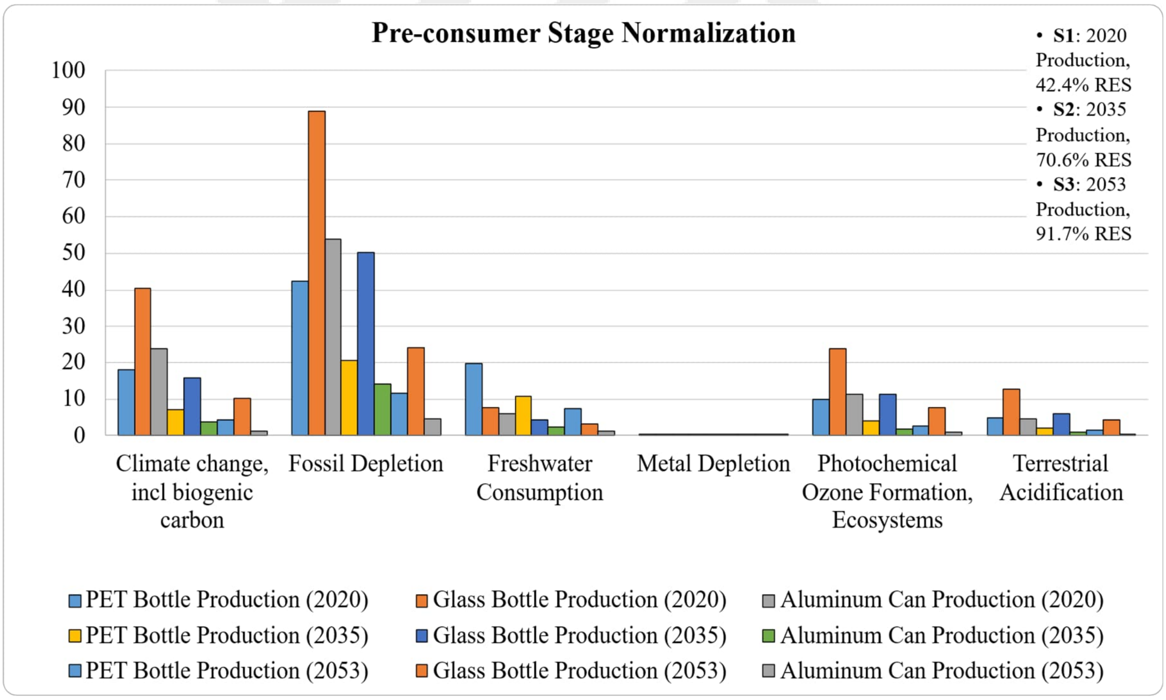

Figure 4.3. Normalization results of the pre-consumer stage

As mentioned earlier, within the context of this study, the post-consumer phase of aluminum does not proceed in the same way as that of PET and glass. Figure 4.4 below reveals the normalized results for the post-consumer stage. However, in terms of impact significance, Fossil Depletion has the highest impact for all years of each product in the post-consumer stage. Additionally, the second-highest impact category for S4 and S5 is Climate Change, except the S5 scenario of aluminum. For all product types, like the production phase, Metal Depletion has the lowest share.

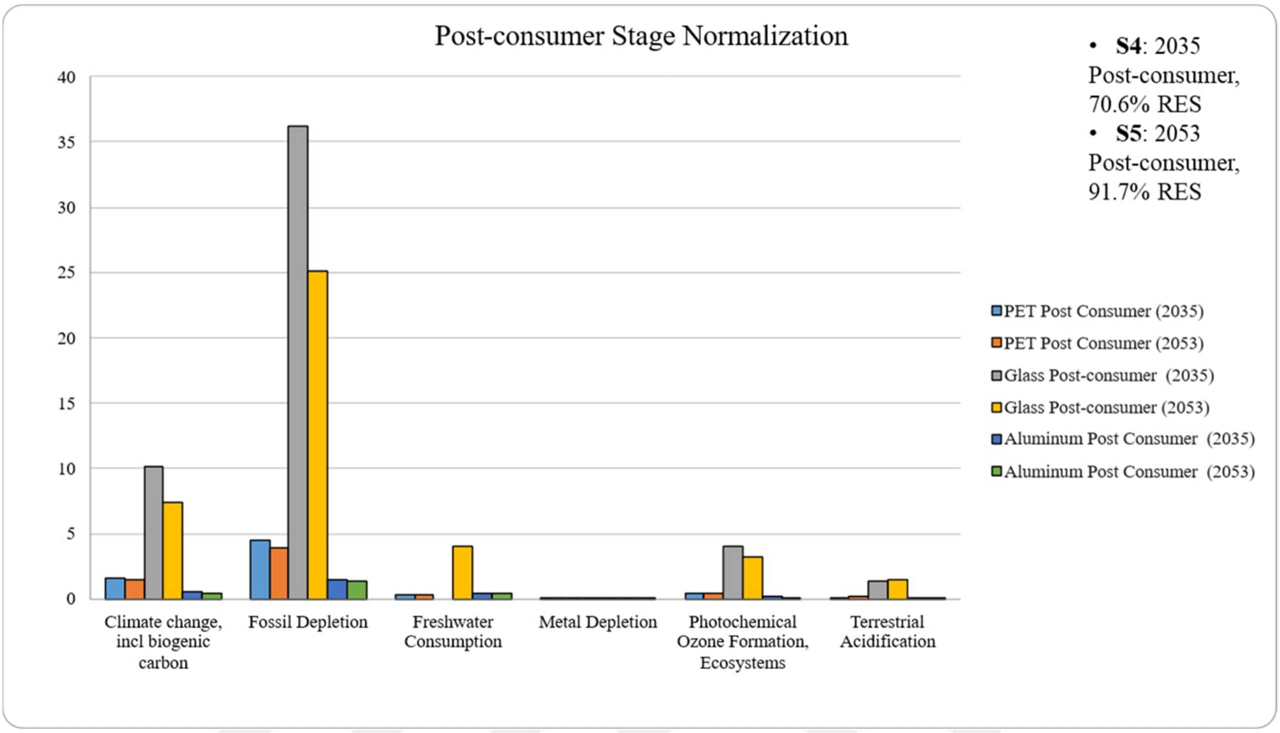

Figure 4.4. Normalization results of the post-consumer stage

4.1.4. Weighting

Weighting provides a more comparable interpretation of the results and support for informed decision-making. The results obtained in the normalization step are multiplied by weighting factors (in %), which can reflect the relative importance of the respective impact categories (Cristobal-Garcia et al., 2016). In this step, according to the selected ReCiPe 2016 v1.1 method, only the endpoint impact categories were examined.

According to the results in Figure 4.5, when the endpoint category is analyzed, decreases were observed over the years, except for the Metal Depletion [$] impact for PET. From S1 to S2, the Metal Depletion impact of PET decreased but from S2 to S3, the result of this impact increased. This impact result increased due to the increasing renewable electricity share. Moreover, glass has the highest impact in all categories except for Freshwater Consumption [species.yr].

For S4 and S5, as illustrated in Figure 4.6, considering the comparison of PET and glass products, within the relevant system boundaries, the post-consumer stage of the PET products has a lower environmental impact (in terms of human health, ecosystem and monetary equivalent) than the glass products. On the other hand, for each product, Climate Change [DALY], Fossil Depletion [$] and Photochemical Ozone Depletion [species.yr] showed decline from S4 to S5.

Figure 4.5. Weighting results of the pre-consumer stage

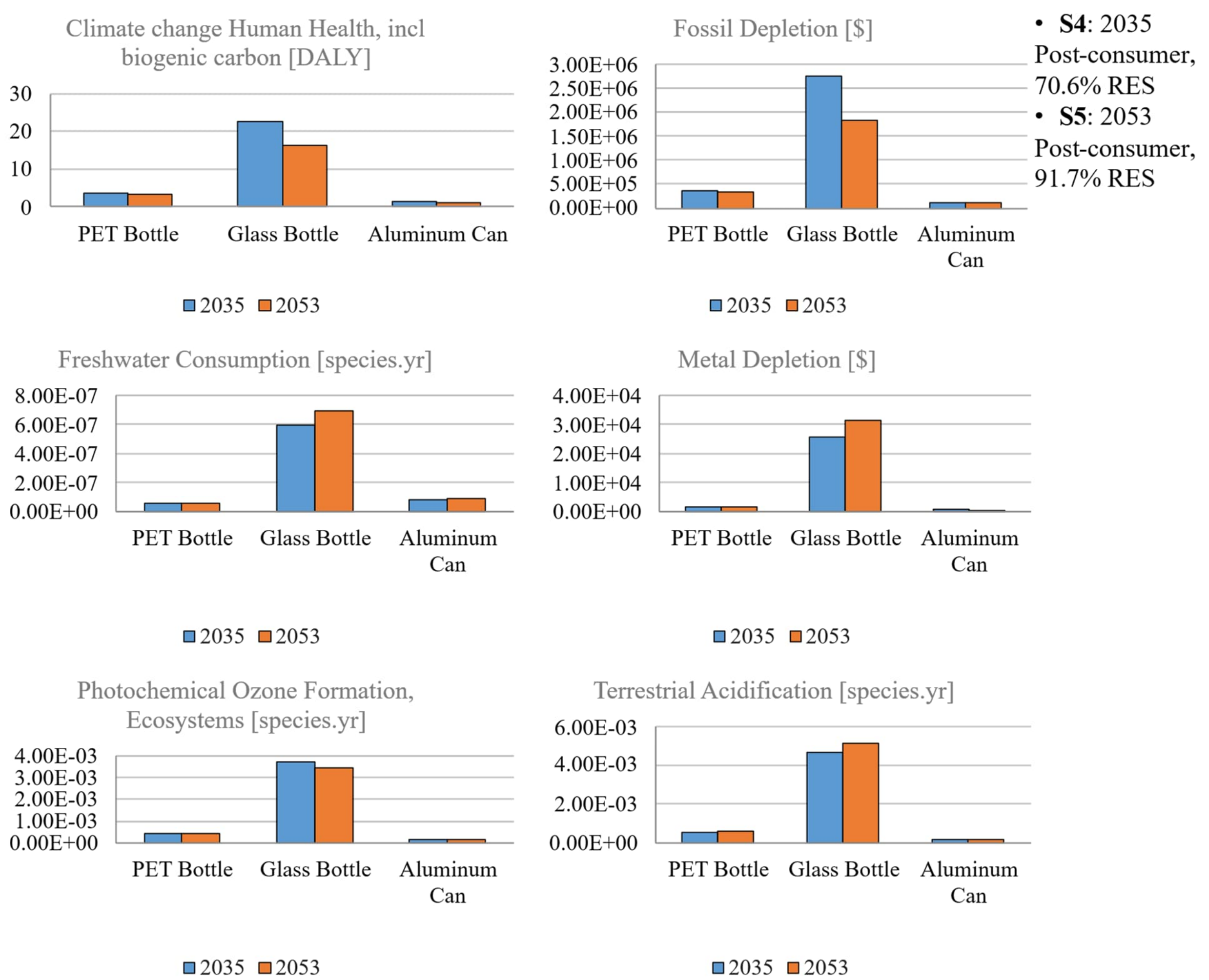

Figure 4.6. Weighting results of the post-consumer stage

4.2. Sensitivity Analysis

A sensitivity analysis was conducted manually to examine the impacts of recycling and reuse separately. The following path was followed: In Chapter 4.1, after producing 1 million products, recycling, reuse, incineration, and landfill processes were applied based on the varying ratios. Unlike Chapter 4.1, the recycling and reuse impacts were specifically analyzed during the sensitivity analysis by providing 1 million product input for each assessed process.

4.2.1. Characterization

In Figure 4.7, characterization calculation results are presented and each impact category was discussed in the following.

4.2.1.1. Climate Change. Evaluation of the Climate Change impact for S6 and S7; on one hand, the environmental effects of glass recycling are the highest, on the other hand, PET reuse has the lowest environmental impact. In a product-based comparison, glass proved to be more impactful than PET. Additionally, comparing the recycling options for PET, open-loop recycling is more environmentally harmful than closed-loop recycling (this outcome is the same in all following impact categories assessed within the study). Considering S2 and S6, glass reuse is preferable to glass remanufacturing and glass recycling. The reductions in the Climate Change impact category in Figure 4.7, from S6 to S7, are as follows: 9%, 13%, 14%, 0% and 45%, respectively. When the results are examined in light of the literature, although Hamade et al. (2020) stated that PET reuse has less environmental impact, according to Tenhunen-Lunkka et al. (2024), Lemos Junior et al. (2019) and Petcore Europe Reuse Working Group (2023), health concerns and material durability are very important in the reuse of PET. On the other hand, according to the study conducted by Chairat and Gheewala (2023), closed-loop recycling should be preferred over open-loop recycling in terms of both environmental impact and product quality. Finally, in the study conducted by Ferrara et al. (2021), which also used the ReCiPe method, the authors particularly emphasized the reuse of glass bottles and the importance of using recycled PET resin.

4.2.1.2. Fossil Depletion. Even though glass recycling has the highest impact, similar to the Climate Change impact, the most notable change occurred in the Fossil Depletion impact category. The declines (except for glass reuse), according to Figure 4.7, are 12%, 16%, 21 % and 46% respectively.

4.2.1.3. Freshwater Consumption. For the S6 and S7 scenarios, declines occurred; however, there are no essential differences between these scenarios due to the overall process and cooling water requirements in both reuse and recycling. From open-loop recycling PET recycling to glass recycling, as presented in Figure 4.7, the decrease changes (except for glass reuse) are 5%, 6%, 3% and 7%.

4.2.1.4. Metal Depletion. In this impact category, considering the transition from the S6 scenario to the S7 scenario, it was noticed that the environmental impact increased in all other processes (except for glass reuse). The increase in the relevant impact category in Figure 4.7 is as follows (except for glass reuse): 40%, 43%, 42%, and 81%, respectively.

4.2.1.5. Photochemical Ozone Formation. As a consequence of the Photochemical Ozone Formation assessment, when comparing scenarios S6 and S7 from Figure 4.7, there is a reduction (except for the glass reuse process) of 6%, 7%, 4% and 18%, respectively. Similar to the Climate Change impact, glass recycling causes the most environmental damage while PET reuse has the lowest environmental impact.

4.2.1.6. Terrestrial Acidification. There is no significant difference for each product comparing S6 and S7 scenarios. When the S7 scenario is applied instead of the S6 scenario, there is a 0.54% decrease for closed-loop PET recycling, while 0.5% and 3.24% increases occurred for open-loop PET recycling and glass recycling, respectively.

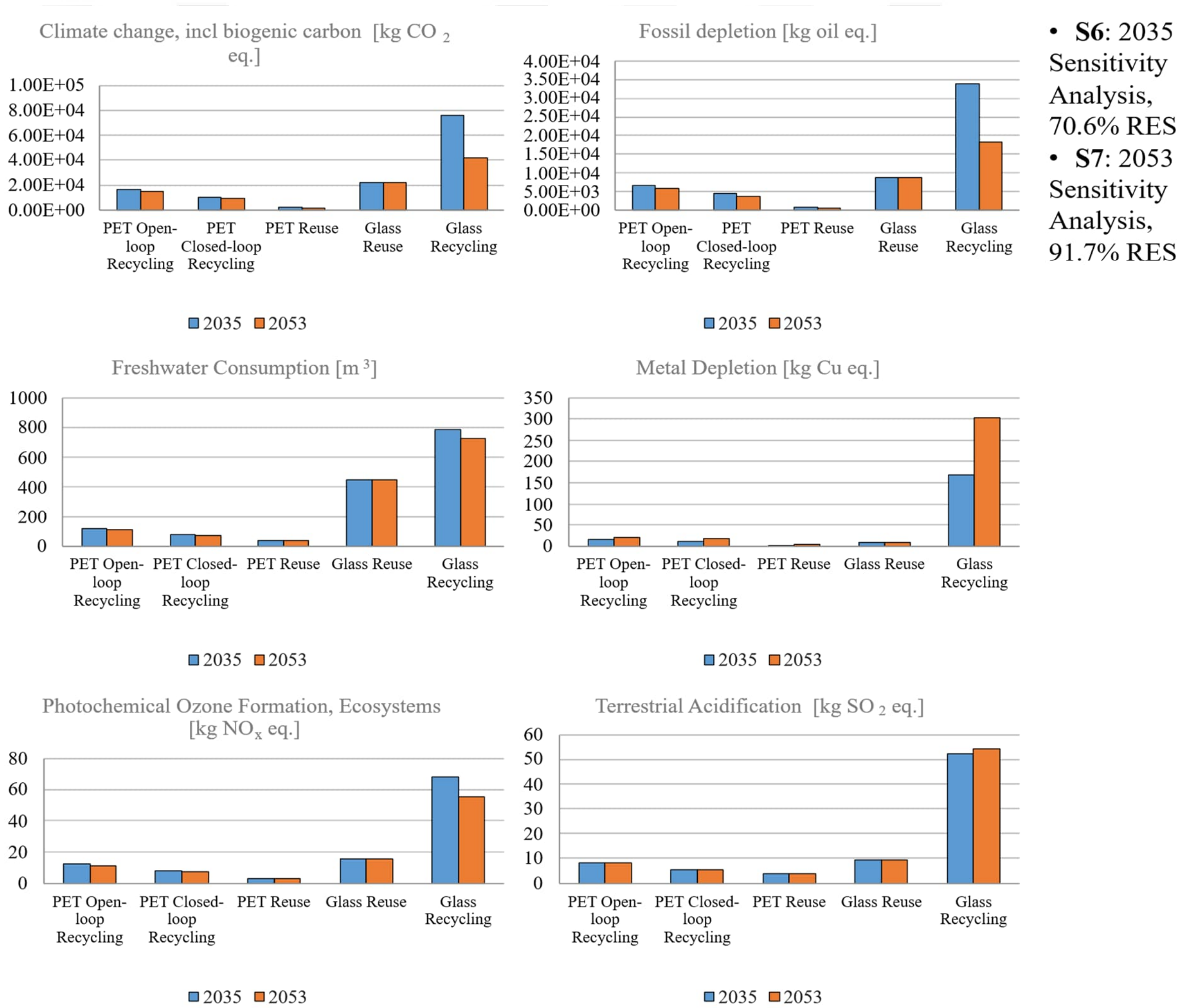

Figure 4.7. Characterization results of the reuse and recycling (PET and glass)

4.2.2. Normalization

The calculated normalized values showed that the highest impact for S6 and S7 is on Fossil Depletion. When the recycling and reuse scenarios of PET and glass are compared, the second-highest impact share is Climate Change. The lowest impact share for S6 and S7 is Metal Depletion.

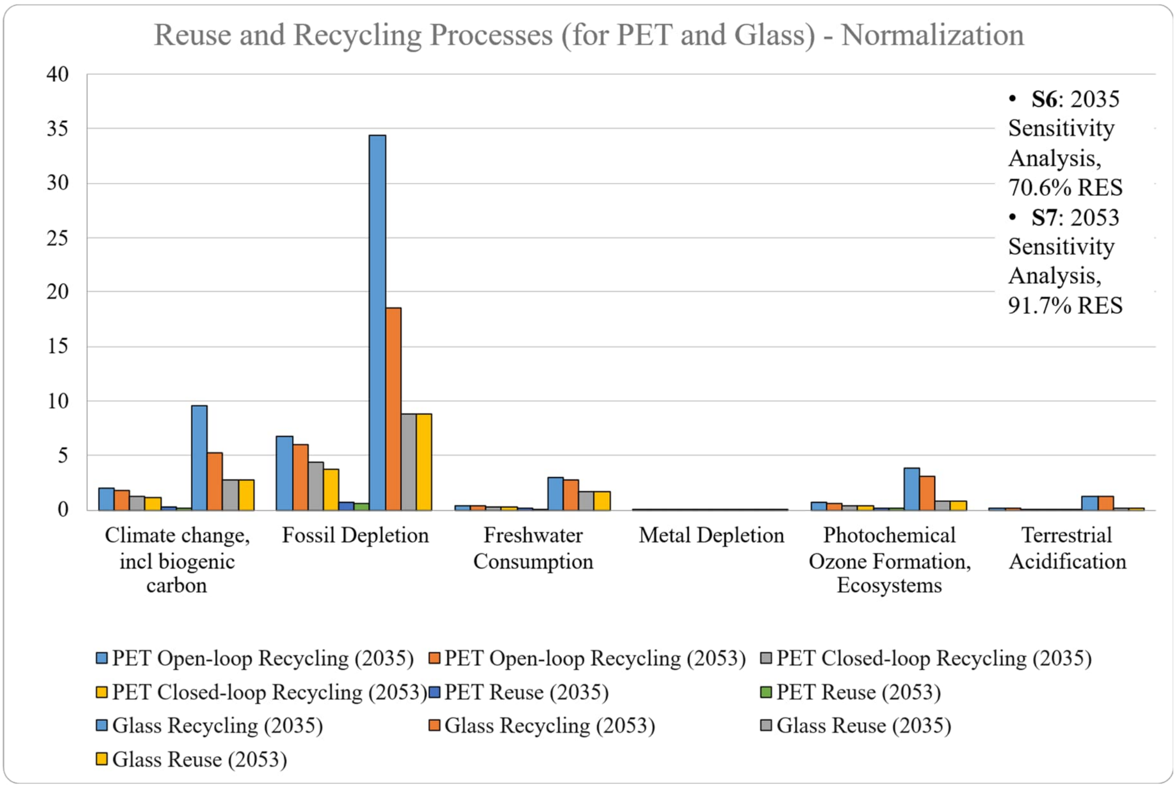

Figure 4.8. Normalization results of the reuse and recycling (PET and glass)

4.2.3. Weighting

From S6 to S7, the impact results of Climate Change, Fossil Depletion, Freshwater Consumption and Photochemical Ozone Depletion decreased. The order of impact results (except for Metal Depletion) is as follows, from high to low: glass recycling, glass reuse, PET open-loop recycling, PET closed-loop recycling and PET reuse. For Metal Depletion, from high to low, the order of these results is glass recycling, PET open-loop recycling, PET closed-loop recycling, PET reuse and glass reuse processes. For glass scenarios, compared to S6 and S7, the Terrestrial Acidification impact in the S7 scenario is slightly higher than in S6. In the S7 scenario, Metal Depletion has apparently more impact in all scenarios. However, in weighting, Fossil Depletion and Metal Depletion are monetary values; considering scenarios S6 and S7, the decrease in Fossil Depletion from scenario S6 to S7 is greater than the increase in Metal Depletion from scenario S6 to S7.

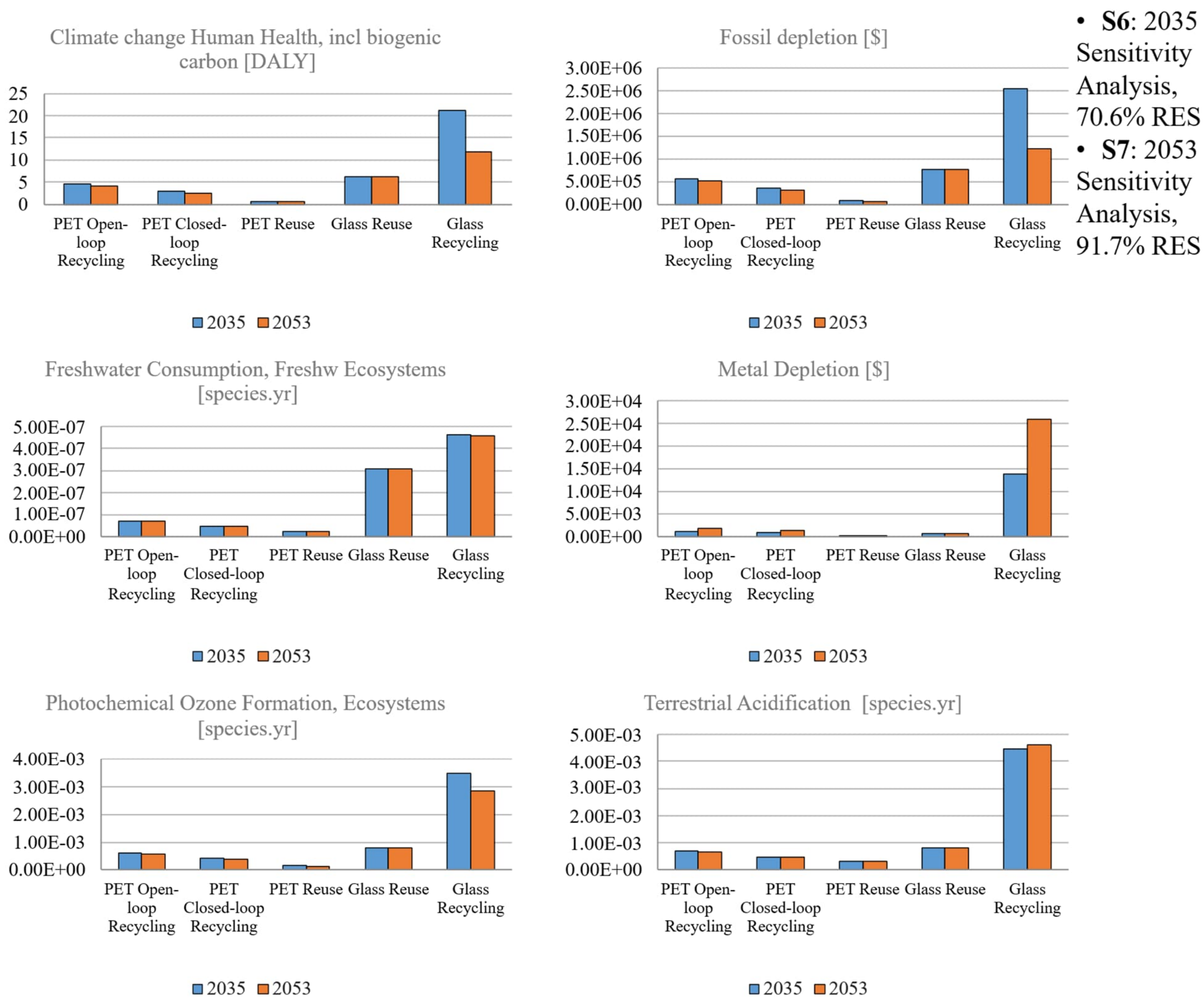

Figure 4.9. Weighting results of the reuse and recycling (PET and glass)

5. CONCLUSION AND RECOMMENDATIONS

The main objective of this study is to examine how the environmental impact of the reuse and (mechanical) recycling processes, especially in the post-production stage, as well as changes by increasing the recycled content in the production stage, steam cracking for PET, and electrification in the melting process for glass and Bayer Process stage for aluminum. For all scenarios involving the pre- and post-consumer stages of soft drink packaging materials, the projected increase in the use of renewable electricity generation in Turkey over the years was also taken into consideration.

Initially, for pre-consumer use, the 16% naphtha yield in the pre-consumer stage of PET, combined with the high energy and cooling water requirements for intermediates, causes environmental and economic inefficiencies. For glass, the use of high thermal energy in the melting process and the Bayer process for aluminum production results in high energy consumption. In this direction, the use of recycled content, electrification in targeted processes, and the utilization of renewable electricity must be supported under optimal conditions.

Secondly, for the reuse of PET in the post-consumer stage (RefPET), human health and durability concerns must be particularly considered. This study examined both the reuse and recycling phases to assess their environmental impact. Although PET mechanical recycling is a more customary practice in a post-consumer approach, refillability has been also targeted, even if it is in its infancy. However, unlike glass, PET reuse requires proper temperature control during the washing phase, as well as additional measures and precautions regarding the chemical release of PET during the washing and other health concerns. As an additional recommendation, analyses should be focused on the improvement of chemical recycling of PET. Furthermore, glass recycling generally results in lower energy use during its remanufacturing because the use of cullet instead of primary raw materials reduces energy use. Glass recycling and remanufacturing generally results in higher energy use than reuse since the production of glass involves a batch process from the beginning for bottle production, unlike PET and aluminum. In addition, efforts must be made to reduce water usage associated with the operational processes involved in the reuse/washing of packaging material. Since reusability is not very possible for aluminum, recycling targets were focused on. In this direction, recycling processes for aluminum must be improved.

Electrification in the selected stages of production processes - in addition to implementing electricity generation with high renewability and recycled content - Fossil Depletion (the highest share in normalization), Climate Change and Photochemical Ozone Depletion demonstrates significant decreases. However, the electricity generation phase requires subsequent infrastructural and systemic improvements to achieve more efficient results. In detail, the Terrestrial Acidification impact category decreases with an increase in the share of renewable electricity. At the same time, a significant decrease is observed at this point, especially when switching from heavy fuel oil (as thermal energy) to electricity, while a slight increase can be noticed in the transition from natural gas (as thermal energy) to electrification. The Metal Depletion impact category increases due to both the transition from thermal energy to electrification and the increase in renewability in electricity generation. If we examine the Freshwater Consumption impact category in terms of electrification at the pre-consumer stage, the use of cooling water in the production phase of the product decreases with the electrification of the relevant process. However, when the energy source is evaluated within itself, a decrease is achieved in this impact category due to the increasing renewability, while an increase occurs in this impact category in the transition from thermal energy to electrification.

Additionally, this study did not focus on improving thermal energy processes and in this regard, observations and LCA practices also must be conducted on the use of the most efficient source where thermal energy is required in the production of soft drink packaging materials. At the same time, within a similar scope, another emphasis is that steps must be taken to improve both product quality and process infrastructures in production, reuse and recycling processes.

Moreover, when the study is evaluated in the context of the deposit return system, it has been addressed in the literature that important steps have been taken in Europe to avoid challenges in this regard. For instance, in Turkey, although certain measures have been implemented, it is significant for local governments to develop a robust waste collection system for the post-consumer phase in terms of waste management strategy. Infrastructural or logistics-related limitations that are part of this process must also be improved locally. From an economic perspective, in line with EPR and circular economy, a more transparent approach must be adopted by assigning both well-defined financial and physical responsibility to the producer side to ensure that the process is not seen as a financial burden.

Briefly, creating incentives in the name of the SDG-12, DRS, circularity, life cycle thinking and redesigning for both pre-consumer and post-consumer stages play a pivotal role in terms of human health, ecosystem preservation and cost-efficiency, as well as the commercial adoption of electrification and increased recycled content in terms of both efficiency and renewability.

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