EVALUATION OF THE ENVIRONMENTAL IMPACTS OF THE SELECTED HOUSEHOLD APPLIANCES VIA LIFE CYCLE ASSESSMENT APPROACH

by

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ABSTRACT

EVALUATION OF THE ENVIRONMENTAL IMPACTS OF THE SELECTED HOUSEHOLD APPLIANCES VIA LIFE CYCLE ASSESSMENT APPROACH

With industrialization, products which make human life more comfortable have become widespread and household appliances having adverse environmental impacts on earth's system through their lifecycle are one of those product groups. On behalf of minimizing the adverse impact of human living on the earth system, the current environmental impact of these products should be measured and analyzed. Since environmental impacts cannot be minimized unless it is measured and analyzed regarding their hot spots. The objective measurement of product groups' environmental impacts is figured out through life cycle assessment (LCA) from cradle to grave within the scope of CML 2001 method by using GaBi 8 software in this study for the use phase having the highest environmental impact in some of the impact categories of dishwashers, washing machines, and refrigerators due to their high electricity consumption. The impact categories with the largest environmental impact include CC, ADP-Fossil fuel, FAETP, HTP, and MAETP, according to the normalization result. The goal of this study is to compare the impact of possible scenarios for circular economy approaches including cleaner electricity mix of Türkiye in 2035, product durability, customer choices, and behavior, and to lessen their environmental burden. As a result of this study, the most environmentally friendly scenarios are the combination of Türkiye's 2035 electricity mix, 20 % fewer washing cycles and 20 % more energy-efficient (S8), and renewing the appliances with 20 % more energy-efficient ones (S5) for Türkiye to achieve its net zero emission target instead of extending lifespan up to 2053.

ÖZET

SEÇİLMİŞ EV ALETLERİNİN ÇEVRESEL ETKİLERİNİN YAŞAM DÖNGÜSÜ DEĞERLENDİRMESİ YAKLAŞIMI İLE DEĞERLENDİRİLMESİ

Sanayileşme ile birlikte insan hayatını daha konforlu hale getiren ürünlerden biri olan ve yaşam döngüleri boyunca dünya sistemi üzerinde olumsuz çevresel etkilere sahip olan ev aletlerinin kullanımı yaygınlaşmıştır. İnsan yaşamının dünya sistemine olumsuz etkilerini en aza indirmek için bu ürünlerin mevcut çevresel etkilerinin ölçülmesi ve analiz edilmesi gerekmektedir. Çünkü en fazla çevresel etkinin kaynaklandığı aşamaları gösteren sıcak noktalarına ilişkin ölçüm ve analiz yapılmadığı sürece çevresel etkiler en aza indirilemez. Bu çalışmada Yaşam Döngüsü Değerlendirmesi (YDD) aracılığıyla GaBi 8 yazılımı ve CML 2001 yöntemi kullanılarak bulaşık makinesi, çamaşır makinesi ve buzdolabının tüm yaşam aşamaları (beşikten mezara) özellikle yüksek elektrik tüketimi nedeniyle en yüksek çevresel etkiye sahip olan kullanım aşaması için bazı çevresel etki kategorileri objektif bir şekilde analiz edilmiştir. Normalizasyon sonucuna göre en büyük çevresel etkiye sahip etki kategorileri CC, ADP-Fosil yakıt, FAETP, HTP ve MAETP olarak tespit edilmiştir. Bu çalışmanın amacı, Türkiye'nin 2035 yılındaki daha temiz elektrik karışımı, ürün dayanıklılığı, tüketici tercihleri ve davranışlarını içeren döngüsel ekonomi yaklaşımları için olası senaryoların etkisini karşılaştırmak ve çevresel yüklerini azaltmaktır. Bu çalışma sonucunda, Türkiye'nin 2053 yılına kadar net sıfır emisyon hedefine ulaşması için kullanım ömrünü uzatmak yerine eşyaların % 20 daha enerji verimli olanlarla yenilenmesi senaryosu (S5) ve Türkiye'nin 2035 elektrik karışımı, % 20 daha az yıkama döngüsü ve % 20 daha fazla enerji verimliliği kombinasyonunu içeren senaryonun (S8) en çevre dostu senaryolar olduğu tespit edilmiştir.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS iii
ABSTRACT iv
ÖZET v
TABLE OF CONTENTS ii
LIST OF FIGURES iv
LIST OF TABLES vi
LIST OF SYMBOLS/ABBREVIATIONS vii
1. INTRODUCTION 1
2. LITERATURE REVIEW 4
2.1. Life Cycle Assessment 8
2.2. Characteristics of Dishwashers Relevant for the LCA 10
2.3. Characteristics of Washing Machines Relevant for the LCA 12
2.4. Characteristics of Refrigerators Relevant for the LCA 17
2.5. Relevant EU Documents for This Study 22
3. MATERIALS AND METHODS 28
4. RESULTS AND DISCUSSION 36
4.1. LCA Results of Dishwasher 36
4.1.1. Clean energy mix comparison (S1 and S2) 38
4.1.2. Durability comparison up to 2053 (S3, S4, and S5) 40
4.1.3. Consumer choice comparison (S2 and S6) 44
4.1.4. Consumer behavior comparison (S2 and S7) 44
4.1.5. Consumer choice and behavior comparison (S2 and S8) 45
4.2. LCA Results of Washing Machine 47
4.2.1. Clean energy mix comparison (S1 and S2) 49
4.2.2. Durability comparison up to 2053 (S3, S4, and S5) 50
4.2.3. Consumer choice comparison (S2 and S6) 54
4.2.4. Consumer behavior comparison (S2 and S7) 54
4.2.5. Consumer choice and behavior comparison (S2 and S8) 55
4.3. LCA Results of Refrigerator 57
4.3.1. Clean energy mix comparison (S1 and S2) 59
4.3.2. Durability comparison up to 2053 (S3, S4, and S5) 60

4.3.3. Consumer choice comparison (S2 and S6) 64
4.4. Evaluation for LCA Results of All Selected Household Appliances 65
5. CONCLUSION 72
REFERENCES 75

LIST OF FIGURES

Figure 3.1. System boundaries of selected household appliances.....29

Figure 4.1. Impact ratio in the total lifecycle according to the characterization results of the dishwasher in Türkiye 2022 electricity mix scenario (S1).....37

Figure 4.2. Change in characterization results for 2035 electricity mix compared to 2022 electricity mix of the dishwasher for each life cycle phases in Türkiye (%). 40

Figure 4.3. Change in characterization results of the dishwasher for durability scenario up to 2053 for S3, S4, and S5. 43

Figure 4.4. Impact change comparison between S2 and S6, S7, and S8 for each impact categories for dishwasher.....46

Figure 4.5. Impact ratio in the total lifecycle according to the characterization results of the washing machine in Türkiye 2022 electricity mix scenario (S1). 48

Figure 4.6. Change in characterization results for 2035 electricity mix compared to 2022 electricity mix of the washing machine for each life cycle phases in Türkiye (%). 50

Figure 4.7. Change in characterization results of the washing machine for durability scenario up to 2053 for S3, S4, and S5.....53

Figure 4.8. Impact change comparison between S2 and S6, S7, and S8 for each impact categories for washing machine (%).....57

Figure 4.9. Impact ratio in the total lifecycle according to the characterization results of the refrigerator in Türkiye 2022 electricity mix scenario (S1). 58

Figure 4.10. Change in characterization results for 2035 electricity mix compared to 2022 electricity mix of the refrigerator for each life cycle phases in Türkiye (%). 60

Figure 4.11. Change in characterization results of the refrigerator for durability scenario up to 2053 for S3, S4, and S5. 63

Figure 4.12. Summary of impact change comparison between S2 and the other scenarios for 1 year impact through all lifecycle phases. 68

LIST OF TABLES

Table 2.1. Analysis of the LCA studies for selected household appliances.....21

Table 2.2. Previous LCA data for selected household appliances. 22

Table 3.1. Impact categories analyzed in the CML 2001 Method. 30

Table 3.2. Data references of all selected appliances in their life cycle. 31

Table 3.3. Electricity generation estimations adopted and calculated from the 2022 Türkiye Energy Balance Table and National Energy Plan.....32

Table 3.4. End of life assumptions and amount for all selected household appliances. 33

Table 4.1. EU documents related to the scenarios developed considering circular economy pillars analyzed in this study. 71

LIST OF SYMBOLS/ABBREVIATIONS

ABS	Acrylonitrile Butadiene Styrene
ADP	Abiotic Depletion Potential
CFC	Chlorofluorocarbons
CO_2	Carbon Dioxide
COD	Chemical Oxygen Demand
EJ	Exajoule
EP	Eutrophication Potential
EU	European Union
FAETP	Freshwater Aquatic Ecotoxicity Potential
GHG	Greenhouse Gases
GWP	Global Warming Potential
HFC	Hydrofluorocarbons
HTP	Human Toxicity Potential
LCA	Life Cycle Assessment
MAETP	Marine Aquatic Ecotoxicity Potential
MJ	Megajoule
MTOE	Million Tonnes of Oil Equivalent
ODP	Ozone Layer Depletion Potential
POCP	Photochemical Oxidant Formation Potential
PP	Polypropylene
PVC	Polyvinylchloride
TETP	Terrestrial Ecotoxicity Potential
UK	United Kingdom

1. INTRODUCTION

Global electricity demand has increased by 6 % in 2021 and it was the largest annual expansion in absolute terms as over 1,500 TWh. Almost half of the global growth has been seen in China where 10 % of demand increase was estimated. The industrial sector represented most of the demand growth, followed by commercial and services sector and the residential sector, respectively. When the power supply does not match the steep demand growth due to fuel shortages, supply interruptions might be seen in some countries. While residential demand grew by between 1 % and 2 % in 2020 and 2021 despite of the reduction in overall economic activity during Covid-19 pandemic in America's region, electricity use increased by over 3.5 % in 2021 and it is estimated that this increase will continue with a rate of 2 % during 2022-2024 period because of rising demand with the population growth in Middle East region (International Energy Agency, 2022).

While the world's total final energy consumption was 414 EJ, electricity consumption per capita was 2,911.5 kWh in 2018 (United Nations, 2021). Households use energy covers the space and water heating, space cooling, cooking, lighting, electrical appliances, and other end-uses (European Commission, 2022b). Households energy consumption was 84 EJ in total corresponding to the sources as 3.2 % for coal, 13.6 % for oil, 28.2 % for natural gas, 28 % for biofuels and waste, 25.7 % for electricity, 5.9 % for heat in 2018 (United Nations, 2021). Retail electricity purchases corresponded to 43 % of total household sector energy consumption in 2020 in the United States because of electricity usage in almost all homes (U.S. Energy Information Administration, 2021). The household sector represented 26.3 % of the final energy consumption or 16.9 % of gross inland energy consumption in the European Union (EU) (European Commission, 2022b). Regarding the breakdown of primary energy consumption in Türkiye for 2017, the highest consumption was residential and services sector with 24.8 %, and industry sector with 24.4 % (Turkish Ministry of Environment, Urbanization, and Climate Change n.d.).

There are some factors which have impacts on the amount of energy for household usage covering geographic location and climate, type of home and its physical characteristics, number, type, usage time and efficiency of home appliances, and the number of household members. To illustrate, larger homes and households are prone to use more energy than smaller homes and households (U.S. Energy Information Administration, 2021).

According to the data for the appliances in U.S. homes by housing unit type, the percent of total housing units for refrigerators, washing machines, and dishwashers were 99.5 %, 84.2 %, and 72.7 %, respectively (U.S. Energy Information Administration, 2022). As a result of the study conducted by Düzgün, Köksal, and Bayındır (2022) for Türkiye, total stock amount for dishwashers, refrigerators, and washing machines are 23,221,218 units, 22,851,661 units and 22,687,596 units respectively in 2018. Those three household appliances have the highest stock amount including deep freezers, tumble dryers and air conditioners. Furthermore, the production amount of washing machines, dishwashers, and refrigerators were 7,660,674, 6,858,117, and 8,283,338 in 2022 and these corresponded to 23 %, 21 %, and 25 % of the total household appliances, respectively (TURKBESD, 2023). Thus, these household appliances are selected to be analyzed in depth while regarding their environmental impacts in this study.

While analyzing the environmental impacts of dishwasher, washing machine, and refrigerator to support sustainable consumption and production, circular economy concept stating that reducing the production-consumption system's inputs of virgin materials and energy, waste, and emissions outputs (physical throughput) through the use of material cycles and energy cascades based on renewable resources is the environmental goal of the circular economy which promotes to reduce, reuse, recycle, recovery, redesign, and remanufacturing instead of take-make-dispose is considered in this study. The economic goal of circular economy is to decrease the energy and raw material costs through production and consumption phase (Korhonen, Honkasalo, and Seppälä, 2018). Since the use phase has the highest environmental load because of the high electricity consumption for dishwasher (Binstock et al., 2013; Van Hoof et al., 2013; Zhifeng et al., 2012), washing machine (Sigüenza et al., 2021), and refrigerator (Gasia et al., 2021), in depth analysis for the use phase is conducted while regarding the extending lifespan, cleaner electricity mix, and consumer behavior and choice in the study.

This study aims to assess changes in the environmental impacts of dishwasher, washing machine, and refrigerator product groups by reflecting on Türkiye’s 2022 and 2035 (estimation for future) electricity generation mix, durability, possible consumer choice, and behavior via LCA. The consideration that has been done for electricity mix regarding the document, which was announced by the Turkish Ministry of Energy and Natural Resources National Energy Plan, based on Türkiye's 2053 Net Zero Emission Target, covering the years through 2035 (Ministry of Energy and Natural Resources, 2023b). Furthermore, Türkiye's Green Deal Action Plan, Regulation on Energy Labelling, and Energy Efficiency 2030 Strategy and National Energy Efficiency Action Plan (2024-2030) are

taken into consideration to determine the baseline for the development of LCA scenarios. Therefore, this study focuses on exploring how various future scenarios will impact the environmental footprint of household dishwashers, washing machines, and refrigerators in Türkiye through the implementation of circular economy principles, encompassing cleaner electricity mix, extended product lifespan, and possible improved consumer choices/behavior.

The significance of this study is examining Türkiye's actual electricity mix data for 2022 and the actual electricity mix estimation of Türkiye in 2035, and analyzing the environmental impacts of using durable products changing the energy efficiency until 2053 for Türkiye. According to the results of the study, the environmental impact of the combination of 20 % washing cycle reduction and 20 % more energy-efficient appliances with 2035 electricity mix of Türkiye shows the most significant reductions as 20 % to 35 % in all impact categories for washing machine, dishwasher, and refrigerator. For Türkiye to meet its net zero emission target, analysis of this study shows that all appliances must be replaced with 20 % more energy-efficient models at the end of their service life, rather than extending their lifespan until 2053 unless the other impact categories FAETP, MAETP, and HTP will be considered because of increasing the impacts. These results might be helpful to have sustainable world by promoting the stakeholders who might be the intended audiences including those involved in the environmental improvement throughout the life cycle of household appliances, eco-designers, manufacturers, scientists, policymakers, and consumers.

2. LITERATURE REVIEW

Considering the residential site electricity consumption by end use in U.S. in terms of 2015 data, 7 % of total electricity was consumed by refrigerators, 0.6 % of total corresponded to dishwashers, and 0.4 % of total corresponded to washing machines (U.S. Energy Information Administration, 2019). Türkiye's energy consumption in residential sector rose up by 21.3 % from 2000 to 2018 and energy consumption of large household appliances covering refrigerators, deep freezers, washing machines, tumble dryers, and dishwashers rose up from 1.24 MTOE in 2000 to 2.53 MTOE in 2018. The residential sector is responsible for one-third of global energy consumption and 40 % of CO_2 emissions. Thus, this sector has gained more attention regarding the long-term climate targets, and it is inevitable to consider energy efficiency potential in residential buildings (Düzgün et al., 2022).

When it comes to water consumption, municipal water which is defined as the water used for domestic, household purposes or public services including drinking, cleaning, washing, and cooking has been taken into consideration. Municipal water corresponded to the 11 % of global water withdrawals in 2017 (Ritchie and Roser, 2017). Regarding the consumption of natural resources, it has been seen that water consumption for manufacturing and domestic purposes is prone to increase. Thus, water consumption is a huge concern, and analysis of the consumption has represented that 10.2 % of the water withdrawal in Türkiye was used for domestic purposes in 2018 (Küçükil, 2020). Considering the indoor household use by fixture, almost 16 % and 2 % of water used for domestic purposes corresponded to the washing machine and dishwasher, respectively. Household hot water use percentage for washing machine was 9.7 % and the dishwasher was 4.8 % (DeOreo, Mayer, Dziegielewski, and Kiefer, 2016). Analysis of the average water consumption of household appliances in UK in 2020, washing machine, modern dishwasher, and eco-friendly dishwasher consumed 24 %, 6.7 %, and 4.8 % water per use, respectively (Statista, 2021). Therefore, it is inevitable to integrate sustainable water management covering the protection of water availability and avoidance of the pollution causing the degradation of water quality (Van Hoof, Buyle, Kounina, and Humbert, 2013) into the areas where water is consumed to promote resource conservation.

Household consumption contributes to more than 60 % of global greenhouse gas emissions (GHG) approximately and between 50 % and 80 % of overall material, land and water usage which are not evenly distributed among regions and wealthier nations tend to have highest per capita impact. Both legislators and manufacturers have been giving importance in monitoring and reducing the

environmental impacts of household appliances by enhancing energy efficiency, using more sustainable materials, and managing its waste properly. By this way, they have promoted sustainability as an important requirement for appliance development by extending the lifetime of them for manufacturers while enhancing competitiveness. Yet, it is vital to clearly define the objective of environmental sustainability and address potential challenges to ensure positive impacts on the environment. Furthermore, the measures in impact reduction and requirements of sustainable appliance development increase the manufacturers' competitiveness (Spreafico and Russo, 2020). Even though there is no publicly available information related to the retirement rates of household appliances for Türkiye, the study of the Ministry of Energy and Natural Resources showed that all appliances are retired around 22 years of their lifespans (Düzgün et al., 2022) and there are researches given in the Table 2.2 mentioning various lifespan. Considering the drivers of energy consumption in residential sector, the main drivers for household appliances are demographics, economic factors, and individual factors covering consuming behavior, technology, and lifestyle (Xu and Ang, 2014).

As mentioned in EU Green Deal, environmental challenges including loss of biodiversity, climate change, and deforestation can be dealt with by providing resource efficiency and a competitive economy while mobilizing industry for a clean and circular economy (European Commission, 2019). The circular economy includes the reduction in GHG while promoting reuse, remanufacturing, refurbishment, repair, and producing energy and material from waste during its life cycle (Korhonen et al., 2018). This approach also connects with the circular economy due to its aim for resource conservation through energy efficiency, decreasing water consumption, or using materials sustainably. Circular economy aims to promote the sustainability of any product and services, and it is a novel approach to create value by extending product lifespan through better design and service while shifting waste from the end of the supply chain to the beginning, allowing resources to be used more effective way by minimizing and reusing more than once. Thanks to circular economy, products are designed for longevity, reuse, recyclable, and resources for new products are derived from old ones. In other words, everything is reused, remanufactured, recycled back into raw material, utilized as a source of energy, or disposed as minimum as possible. Governments encourage and, in some cases, mandate the adoption of circular economy ideas and practices that will result in greater resource efficiency and reduced waste. This also complies with the Sustainable Development Goals (SDGs) accepted by United Nations Member States in 2015. Ellen MacArthur Foundation estimates that circular economy business models might save $1 trillion in materials costs each year by 2025. Through resource recovery and remanufacturing, national economies, entrepreneurs, and

employees will profit as they build new firms and generate new employment created by circular economy. The main approaches for circular economy are given as follows (UNIDO, n.d.):

- Green products (non-toxic, long-life, recyclable)
  - Proper selection of household components lessens the impact and aims to quantify the feasibility to minimize domestic effects just by choosing different domestic components for policymakers, manufacturers, and consumers while promoting, producing, and purchasing appliances (Spreafico and Russo, 2020).
- Recycle waste, reuse resources
  - Proper recycling and reuse of the materials used in household appliances save not only materials and resources but also money to be spent for extracting new material.
- Collect at the end of life, remanufacture
  - Collecting and remanufacturing household appliances which is not able to use anymore improve the recyclability and reusability of the appliances.
- Better service (to extend lifespan)
  - Repairing the malfunctioning household appliances prevents the excessive use of the resources by extending the lifespan.
- Cleaner production (using fewer resources)
  - Improvements in energy management and environmentally friendly user behavior reduce the environmental impacts. If any adjustments can improve the situation compared to the potential benefits of using domestic components, policymakers and consumers might make adjustments about the solutions for reducing environmental impacts (Spreafico and Russo 2020).

It is vital to evaluate durability which refers to the ability to last its lifespan is becoming increasingly crucial within the scope of the EU policies in terms of the circular economy to enhance product design and manufacture to achieve resource savings and waste minimization. There are many factors must be considered for durability as practical limits on lifetime from current manufacturing methods, cost of the new implications, components, and manufacturing to extend lifetime, innovation rates, consumer habits on product performance, the availability and acceptance of appropriate standards, and the testing methods for enhanced durability. As mentioned in a study, the determination of the product lifetime can be achieved by users, not by the manufacturers. The impact of consumer behavior on the product's durability is vital as how the product is used might degrade or restrict the product’s lifetime compared to the manufacturer’s responsibility. Just extending a product’s lifespan may not necessarily mean in the best environmentally friendly approach. The

efficiency of the worn-out products as well as the technical advancement may influence the impact of lifespan extension which may not always appear to be the best plan. The extension of the lifetime results in the environmental benefits for the impact categories contributed by the manufacturing phase such as freshwater ecotoxicity and mineral, fossil, and renewable resource depletion if energy efficiency is not considered. Regarding the energy consumption during the use phase, there is a slight benefit in the replacement of the product with the energy-efficient one as less than 10 %. While considering the economic point of view, more durable products are practically always the preferred choice for consumers, and it is not always the environmentally friendly option. If the production and end of life stage have the highest impact compared to the usage phase which means very low energy consumption during the use phase or there is only minor increase in energy efficiency, it can be preferable for the consumers for both economically and environmentally benefits (Iraldo, Facheris, and Nucci, 2017). As mentioned in the study conducted by Horie (2004), replacing an older and inefficient product with a newer one might be more efficient due to the reduction in energy consumption and emission through the usage phase.

Given the recent environmental difficulties and concerns about resource scarcity and sustainable development, the circular economy has grown in favor of sustainable production and consumption. Thus, nations throughout the world have started to develop circular economy policies and strategies. For instance, Circular Economy Action Plan which is a building block of the EU Green Deal has been published in Europe (Sigüenza, Cucurachi, and Tukker, 2021). Following this the Turkish Ministry of Trade has released the Green Deal Action Plan addressing the circular economy concept, thanks to Türkiye's economic ties with EU. All appliances will be evaluated within the scope of the circular economy approaches in this research while regarding the through life cycle of the household appliances. As a result of climate-related developments in Türkiye, such as joining the UNFCCC in 2004, the Kyoto Protocol in 2009, and the Paris Agreement in 2021, Türkiye has increased its involvement in international efforts to combat climate change and taken steps to fortify its domestic policies related to the issue. As a result, Türkiye provided the UNFCCC Secretariat with its first intended nationally determined contribution (INDC) in 2015. Later, Türkiye released its revised NDC along with new goals for mitigating climate change in November 2022. Türkiye's mitigation goal for 2030 has grown from 21 % in 2015 to 41 % with its recent NDC. The year 2038 was chosen as the year when emissions would peak, with a target emission level of 695 million tons of CO_2 equivalent in 2030. This target is an important increase in ambition based on science and equity and a step forward toward to long-term objective of achieving a net zero target by 2053 (Republic of Türkiye,

2022). To achieve these targets, sustainable resource management plays a crucial role and household appliances have a direct impact on resource management.

2.1. Life Cycle Assessment

As known, human-made activities which have adverse impacts on the environment cause challenges as climate change and resource depletion. The relationship between these environmental problems, social and economic challenges provide the basis of sustainable development which meets today's needs without compromising the future generations' needs. To meet the SDGs and targets, the decision which regards solutions for the environment, economy, and social challenges should be supported. To comply with the environmental sustainability for any product, process, system while regarding all environmental impacts from its entire life stages, LCA is a tool as quantitative sustainability assessment to find solutions to present challenges. The methodology of LCA follows the International Organization for Standards (ISO) 14040 and 14044 as its principles, framework, requirements, and guidelines (Hauschild, Rosenbaum, and Olsen, 2018).

Measuring environmental impacts accurately has a crucial role in sustainability. LCA methodology has gained a lot of attention as a useful technique for examining the environmental burden of a product or service across its entire life cycle from raw materials and energy usage to production, use, and disposal (Yamaguchi, Seii, Itagaki, and Nagayama, 2011). LCA might be used by business, government, and non-governmental organizations for strategic planning, priority setting, and product or process design or redesign (Cullen and Allwood, 2009). Most of the companies across different geographical areas are aware of the significance of achieving favorable environmental performance to ensure their future success and actively take measures as implementing cleaner technologies and making modifications to their products to minimize environmental impacts. Understanding the environmental performance of a product can be achieved by LCA to evaluate the environmental attributes of the product (Nielsen and Wenzel, 2002). Moreover, adopting the LCA approach has the potential to identify product improvement opportunities, provide information for decision-makers, and facilitate the selection of environmental performance indicators and marketing strategies. It is vital that prioritizing is dependent on the intended application of LCA and comparability of studies related to this methodology can be achieved by matching assumptions and study environment with the reference system boundary (Cullen and Allwood, 2009). This methodology is one of the most useful tools to quantify and evaluate the sustainability of current technologies while comparing environmentally friendly options and newly developed technologies

and facilitating critical discussions on eco-design choices (Hauschild et al., 2018; Spreafico and Russo, 2020). LCA is also used to determine the most important environmental impacts as foundation for creating minimum set of basic criteria for awarding an ecolabel voluntarily. Provision of environmental impact information to customers can be achieved through ecolabeling, designed to give a system for conveying information to customers about the items regarding their fulfillment of high environmental performance requirements. By this way, manufacturers bring life cycle thinking into the public consciousness. One of the product groups for which criteria were defined is washing machines and the entire environmental effect has been classified as consumption of energy, pollution of the air, water contamination, waste management, and water consumption. Ecolabeling requiring political support applies to the current product groupings and avoids making value judgments. Applying LCA to ecolabeling has faced several practical issues and limits of LCA as related to the problems in transitioning from inventory to assessment and provides a barrier for LCA practitioners (Clift 1993).

Even though the LCA studies play a crucial role for examining the environmental impacts of any product, there are some limitations while conducting the well-established LCA research as follows:

1. Limited time coverage due to consideration of the current situation and not able to consider the appliance trends in the future. This might cause fading the importance of this study (Spreafico and Russo, 2020).
2. Limited geographical coverage due to consideration of the specific countries and not able to encompass other regions worldwide since climate and resource availability affect the environmental impacts of the appliances (Spreafico and Russo, 2020).
3. Limited consideration of ethnographic habits due to different levels of environmental awareness of the consumers varying from country to country in use phase (Spreafico and Russo, 2020).
4. Limited technology coverage due to consideration of available appliances without regarding other technologies (Spreafico and Russo, 2020).
5. Uncertainty in data sources due to the inclusion of the data for raw material and energy from databases (Yuan, Zhang, and Liu, 2016).
6. Simplified use phase assumptions due to limited available data (Yuan et al., 2016).
7. Limited data availability for end of life phase due to limited first-hand data availability and heavily on literature resources (Binstock, Gandhi, and Steva, 2013; Yuan et al., 2016).

2.2. Characteristics of Dishwashers Relevant for the LCA

Even though there is manual option for washing the dishes, total stock of the dishwasher is still the highest while regarding household appliances in Türkiye (Düzgün et al., 2022). While dishwashers decreased energy consumption by 34 % and water consumption by 30 % between 1990 and 2005, handwashing requires no technology and just energy to heat water. However, using dishwasher is much more environmentally friendly due to its high water and energy efficiency in the literature (Binstock et al., 2013). Therefore, dishwasher usage is also extremely common in developed countries exceeding 60 % in some countries (Zhifeng, Yang, Di, and Bo, 2012).

While water supply and the gas used to heat water are two operations that may influence the environment through handwashing, the water supply, gas used to heat the water, energy used to power the dishwasher, and manufacturing. Since the type of soap or sponges has an impact on the environment, some studies do not cover the possible impacts of soap and sponges for handwashing options (Binstock et al., 2013). According to the study, comparisons of the results of automatic and manual dishwashing were implemented while regarding the sources of energy usage, associated CO_2 emissions, and the cost of the energy consumed and automatic dishwashing consumes less energy throughout its life cycle when compared to manual dishwashing. By this way, it can be concluded that automatic dishwashing results in lower CO_2 emissions (Vivian, Haslam, Soldner, and Sangster, 2011). Whether an individual prefers hand washing or automatic dishwashing, how they wash their dishes ultimately has an impact on how much energy, and water is consumed and GHG is generated. To illustrate, if hand washing is preferred as filling the sink basin with a full load of dishes, the total GHG emissions are lower than preferring dishwasher. Demographic characteristics as age, region, or gender didn’t significantly correlate with whether a person filled the sink or left the water running (Binstock et al., 2013).

According to the study, 90 % (80,900 MJ) of the primary energy used by dishwasher during its use phase, and the 4,300 MJ of the primary energy is consumed during its manufacturing phase with a determined lifetime assumption (Binstock et al., 2013). Therefore, use phase has the highest environmental impact on the dishwashers’ life cycle (Binstock et al., 2013; Van Hoof et al., 2013; Zhifeng et al., 2012).

The working system of the dishwasher during the use phase, for the tableware, starts with the water inflow and in this stage, as a result of the circuit's control, the feed valve opens allowing water

to enter the respirator's input. Mechanical devices separate the water into two streams inside the respirator; one stream stays inside the respirator while the other enters a water softener to soften the water before it reaches the water cup. When the water level reaches the maximum, the pressure switch is opened, and the water intake is completed. The second stage is the washing process where the washing pumps pressurize the hot water and split it into two streams; one path leads to the top washing arm, while another leads to the bottom washing arm. Tableware is being washed by the rotating, high-pressure washing arms. The third stage is drying where the tableware is drying with the use of residual heat of hot water. The last step is drainage whose pump removes the water when the washing is completed (Zhifeng et al., 2012). If prewashing is done before this stage or dishwasher is not washing with a complete load of dishes, dishwasher requires more energy and water and emits more GHG emissions per dish. Instead of pre-rinsing, scrapping food off dishes before loading is enough for most of the dishwasher. It was also discovered that energy consumption to heat the water is the main variable affecting how much energy is used to wash dishes and how much GHG is released. Furthermore, there is a change in water consumption and temperatures depending on the quantity of water used. Moreover, more energy and water are consumed in the older dishwasher and the latest version of the dishwashers are various in their efficiency levels by having number of settings that may change how well dishes are cleaned. While using the most efficient settings used in dishwasher, less energy consumption is described in the user manuals. Yet, it is found that most of the consumers do not follow the user manuals while using dishwasher and more than 90% of respondents rinse the dishes before loading dishwasher in one of the studies (Binstock et al., 2013). Thus, it is important to push consumers to change behaviors for not pre-rinsing and reducing energy and water consumption through use phase (Zhifeng et al., 2012). In addition, there is another factor affecting the quality of the dishwasher and its energy consumption and it is called as cleaning performance index to evaluate the cleaning performance (Sustainable Energy Authority of Ireland, 2023). To calculate this index for a dishwasher model, cleaning performance of the environmentally friendly program is compared with the cleaning performance of a reference dishwasher and the determined value should not be less than the declared value (Government of United Kingdom, 2021).

When dishwasher is no longer useful, it can be separated into different material flows for reuse, recycling, energy recovery, or disposal. Most of the countries were influenced by the EU's environmental legislation to protect environment through regulations or directives on waste electrical and electronic equipment to improve recycling rate and restrict the use of hazardous materials for the products. In most of the countries including Türkiye, manufacturers are in charge of collecting and recycling the used appliances and desire not to lose any valuable materials (Johansson and Björklund,

2010). Within this context, if the dishwasher which cannot be used anymore is to be recycled, it is sent to the disassembly factory to be sent to be remelted and produced raw materials from the metal parts and to avoid the new process of ore mining and metal smelt; and to be sent to incineration plant or recycling plant to generate power and heat from waste plastics by replacing fossil fuels (Zhifeng et al., 2012).

While the most serious impact among the impact categories was detected as marine aquatic ecotoxicity (MAETP) which was affected by the heavy metal and organic matter released in the raw material production and use phase, the second one was the CC which was affected due to the thermal power plants using fossil fuels to power generation in 9 environmental impact categories. Moreover, if the lifetime of the dishwasher is long, the highest environmental impact is caused by the usage stage and the second highest one is raw material production caused by the heat engine plants using fossil fuel (Zhifeng et al., 2012).

2.3. Characteristics of Washing Machines Relevant for the LCA

Washing machine which is one of the most popular household appliances in people's daily lives are currently receiving attention from governments and suppliers because of their resource and energy consumption and emissions related to their production, distribution, use, and disposal (Yuan et al., 2016). Even though washing machine was selected to analysis of this study because of its high usage in Türkiye, it was selected for the research conducted by Sigüenza et al., (2021) because of its frequent usage in testing environmental assessment methods, accounting for roughly one-fifth of the impacts of household appliances in use, materials demand in appliances is expected to double by 2050 and limited scientific literature addressing business models related to circular economy. Thus, it is important to provide scientific knowledge to achieve more sustainable resource management.

There are two types of washing machines named as horizontal axis and vertical axis. While just the bottom of the wash tub is filled with water in horizontal axis machines which are front load washers, the entire tub is often filled with water in vertical axis machines which are top load washers. Horizontal axis machines use significantly less water per wash cycle than vertical axis machines (Pakula and Stamminger, 2010) and are more energy-efficient (Gündüz, 2012). Horizontal-axis washing machine has grown in popularity among customers due to its superior detergency, less clothing abrasion, and improved efficiency across its complete life cycle considering manufacturing technology and consumer habits between countries (Yuan et al., 2016).

The LCA study for horizontal-axis washing machines has been implemented to provide practical proposal to improve the environmental performance of washing machines in China and to provide scientific knowledge for policymakers to achieve environmental sustainability. The manufacturing and use phases have a considerable environmental burden while the manufacturing phase is responsible for 7.7 % of overall TETP effects and up to 80 % of ADP components, the use phase contributes the most of the impact categories ranging from 14.8 % to 91.8 % except for the ADP and ODP impact categories while human activity whose environmental effect exceeds 10 % of the total life cycle impacts in any impact category is considered as a hotspot. The essential procedures in the manufacturing process include injection molding and powder spraying. It was identified that electronics, plastic mold injection, and metal components were the primary hotspots for the manufacturing phase. The degreasing and phosphating processes during the manufacturing phase of washing machines use substantial amounts of surface treatment chemicals such as bonderite and emit a considerable amount of pollutants into the environment. Chlorinated agents which are frequently used solvents for metal degreasing, are thought to be contributors of both GHG and volatile organic compounds. While aluminum and copper use in electronics, ABS use, and power use in injection molding are possible hotspots throughout the manufacturing phase, it demonstrates that the manufacture of aluminum, copper, and ABS is not environmentally friendly, since it releases a variety of toxins into the atmosphere and water and uses fossil resources. Depending on the realistic manufacturing circumstances such as mold temperature and injection duration, the parameters of primary process equipment should be modified to lower the defective rate. In the powder spraying process, high-efficiency dust-collecting equipment should be built to efficiently decrease both cost and emissions (Yuan et al., 2016). To minimize energy and material consumption, on-site management should be reinforced by encouraging energy-saving performance assessment through training and improving employees' professional knowledge and abilities. To save energy, waste heat from the injection molding process should be recycled (Spreafico and Russo, 2020; Yuan et al., 2016).

To deal with the environmental impacts of the detected hotspot, improvement opportunities might be helpful for manufacturer and consumer behavior improvement, supply chain optimization, and product attribute enhancement. For the use phase, environmental education can be helpful for optimization of the consumers' washing habits, such as choosing normal temperature washing mode in summer, washing more clothes with the maximum capacity, and adding appropriate amount of detergent and water depending on the amount of the clothes. Furthermore, there can be improvements covering the electricity mix and cleaner energy such as hydropower and nuclear power to be replaced with thermal power. To conserve the water bodies, new municipal wastewater treatment plants mainly

in villages and towns should be established to lower COD, nitrogen, and phosphorus emissions to the environment (Yuan et al., 2016). According to the LCA study mentioned by Clift (1993), use phase including energy and water consumption, detergent manufacturing and distribution, aqueous waste treatment, and final solid residue resulted in more than 90 % of the environmental impacts. Similarly, it is identified that key hotspots throughout the usage phase were energy and detergent consumption while water temperature is the most contributor to all environmental impact categories excluding ADP and EP due to its electricity consumption. While detergent use and wastewater discharge had the greatest impact on environmental consequences related to ADP, EP, and TETP accounting for 78 %, 77 %, and 91 % of overall impacts, respectively, energy consumption is the key cause of the environmental burdens. Electricity consumption is prominent in each effect category during the usage phase, and cleaner electricity is required for the study conducted in China (Yuan et al., 2016).

While extending the lifespan of items can result in lower environmental impacts and material use, this may not be applicable for energy-intensive products. Thus, it is critical to analyze the potential benefits associated with long-term implementation of circular business models (Sigüenza et al., 2021). Reliable assessment techniques are necessary to produce more durable appliances. Internal testing is common method used by manufacturers to assess an appliance's durability and technical lifetime. The majority of washing machines are replaced due to defects which is obtained from consumer behavior research. In general, washing machines typically need to be replaced after 12 years with 50% breaking down before that time. Washing machine longevity is closely correlated with frequency of use and major failures cover the electronics (control electronics, control panels, program selectors, relays, etc.), shock absorbers, bearings, doors (seals, handles, hinges, and locks), and motors (carbon brushes) (Stamminger, Bues, Alfieri, and Cordella, 2020). Yet, it should be noted that durable products lower energy efficiency raising worries about their environmental effects while having a higher cost-benefit ratio for customers (Sigüenza et al., 2021). Information about the lifetime, annual consumption and use behavior mentioned in the previous research for selected household appliances can be found in Table 2.2.

Consumer behavior has changed in recent years because of changes in family composition and lifestyles, increased usage of automatic washing machines considering environmental impacts and the need to save energy, and changes in detergent choices such as concentrated detergents (Yamaguchi et al., 2011). There is research about the life cycle of washing machines in the Dutch market while considering the production rates, installed bases, material flows and material stocks in several scenarios covering the adoption of product lease and pay-per-wash model, halving detergent

use, and energy transition. It is discovered that cumulative climate change impacts of washing activities would be 35 % lower with a complete adaption of product lease options as launderettes in Europe. If the entire market is captured with a 50 % penetration rate for the launderette, it is discovered that total climate change consequences of washing activities in Sweden might be decreased by 16 % to 29 %. These savings are attributed to extended washing machine lifespans as well as several technology enhancements as energy efficiency and decarbonizing electricity. It is found that the adoption of the circular business models with a high diffusion as a consumer behavior reduces the production rates by 21 % and 28 % in 2050 when compared to the production rates in 2020. Even though, it is thought that circular business models might result in employment opportunities, reduction in production rates might require less labor and this man work may shift from manufacturing to the services sector for the implementation of circular business. For the material uses and stocks, material use might be decreased by 23 % and 3 % in 2050 with a high and slow diffusion variant, respectively. Even though the users may easily use high amount of detergent without auto-dosing systems, the average recommended dose for a washing cycle is 150 to 70 g in the last 20 years. 40 % decrease in detergent use by 2050 might result in 14 % reduction in climate change impact comparing the without any further intervention in 2050. Raising awareness among users about detergent use might be a strategy for creating more sustainable business. For the climate change impacts for all scenarios including circular business models, use phase of washing machines contributes 88 % in the baseline scenario in 2020 and as little as 60 % in the electricity transition scenario in 2050 (Sigüenza et al., 2021).

Promoting the circular business models as pay-per-wash and product lease, access and subscription-based business models might mitigate possibly lower revenues from reduced production rates and subsequent sales for manufacturers. Consumers should use detergent moderately and if there is a need to replace their current washing machine, consumers should prefer a high-efficiency model while remembering that it is long-term investment that should not be changed before 12.5 years to successfully contribute to material usage mitigation. For creators of circular business models, it is suggested to conduct research and build mechanisms to understand customer behavior, as use-feedback systems for both users and company owners, to ensure the capture of environmental and material advantages of circular business models (Sigüenza, 2021).

Quantitative LCA is a useful tool for decision-makers to be familiar with the environmental impacts of washing machines and to explore the opportunities for sustainable improvements as well as to assist manufacturers in identifying priorities for environmental protection (Cullen and Allwood,

2009; Yuan et al., 2016). The regulations have already resulted in substantial advances in energy efficiency in washing machines in China, but users' consumption patterns also have a significant impact on energy and water consumption. It is recommended that policymakers and washing machine manufacturers consider a minimum standard lifetime as at least 25 % longer than the current average of 12.5 years while maintaining the current material intensities of the appliances and including as many dematerialization strategies as possible (Sigüenza et al., 2021). The regulations have already resulted in substantial advances in energy efficiency in washing machines in China, but users' consumption patterns also have a significant impact on energy and water consumption (Yuan et al., 2016). Manufacturers and energy purchasers will be incentivized to pursue energy efficiency improvements within the process system that they manage. The burden of accountability would remain with the control of manufacturer instead of users due to the supremacy of the usage phase (Cullen and Allwood, 2009). Furthermore, studies revealed that customers do not use many energy-saving programs indicated in the energy labels which ought to accurately represent real-world circumstances to conserve energy. In line with the energy consumption shown on the label, energy efficiency index of the washing machine complies with the washing performance index affected by temperature, chemistry, program length, and mechanics. Several combinations of these variables can be used to obtain various levels of washing performance having longer program lengths and lower temperature yields the highest levels of efficiency. Manufacturers found that higher temperatures are not as energy-efficient as longer washing cycles. In general, short programs use more energy and temperature and are not recommended for fully loads. Larger capacity washing machines require longer programs even though they consume less energy and have better energy labels. Consumers often do not use machines with fully load which results in higher energy consumption (Boyano, Espinosa, and Villanueva, 2019).

The washing machine's transportation phase is divided into two stages as transporting washing machines from manufacturers to wholesalers/retailers and distributing washing machines to individual homes. For both phases, the average distance of a washing machine is considered and transportation has little environmental impact (Yuan et al., 2016).

In China, the number of outdated washing machines is expected to be 687 to 708 million units by 2030 and standardized recycling is advantageous for improving resource recovery and mitigating pollution caused by the disposal of washing machines. Given the large number of obsolete household appliances and China's present poor recycling, legislation has been created to enhance the management of refuse electrical and electronic equipment in China. As a result, an increasing number

of old washing machines would have to be collected and recycled. Disassembly, shredding, and separation are among the techniques under consideration in the end of life phase of washing machine. While disassembling a washing machine is a manual process, the wastes are shredded and divided into metals and plastics after disassembly and removal of components such as cabinets. Steel, copper, iron, aluminum, polypropylene (PP), acrylonitrile-butadiene-styrene (ABS), and polyvinylchloride (PVC) are recyclable materials, whereas all other materials are disposed in landfill. It is vital to mention that recycling steel, copper, iron, aluminum, PP, ABS, and PVC might result in recycling credits reflecting a negative value in LCA results due to recovered materials corresponding roughly 86 % of washing machine's overall mass. The end of life phase has no adverse impact while having a recycling credit as positive impact and generates a range of recycling credits ranging from 5 % to 77 % across impact categories. Steel and plastic recycling account for more than half of the total recycling credits. Copper recycling is the third largest contributor and iron and aluminum recycling is small as contributing less than 1 % to most impact categories. All recycling credits are attributable to loads avoided during material manufacture (Yuan et al., 2016).

2.4. Characteristics of Refrigerators Relevant for the LCA

As mentioned before, total stock of refrigerator is the second highest while regarding household appliances in Türkiye (Düzgün et al., 2022). Refrigeration accounts for around 8 % of the GHG emissions (Rossi, Favi, Germani, and Omicioli, 2021). The number of global laws establishing the maximum temperatures for refrigerator to be reached during the manufacture, distribution, and retail sale of chilled food has significantly increased since the late 1980s. Yet, once the food is purchased by the customer, it is no longer subject to these regulatory obligations. After taking the chilled product from the retail it is carried throughout the store and then delivered to home for additional storage. It can be left at room temperature or kept in the refrigerator if needed at home. In recent years, there has been much concern about the role of insufficient temperature control and handling in home due to increasing number of food poisoning incidents. To achieve safe food storage, running temperature for the refrigerator is crucial and according to the UK recommendations on microbiologically safety of foods, maximum temperatures in household refrigerators should not exceed 5°C. The mean temperature range differs among the refrigerator types covering the ice-box, fridge-freezers, and larders. While the older design ice-box refrigerators have a box-plate evaporated to keep frozen food for a limited period, back-plate evaporators are used in larder refrigerators and fridge-freezers having one compressor that supplies both the fridge and the freezer or two separate compressors (James, Evans, and James, 2008). Steam compression refrigeration which comprises a compressor, a

condenser, an evaporator, an expansion device, and interconnecting pipes account for about 17 % of worldwide energy consumption, and improving the efficiency of this high-energy-consuming equipment will help to enhance economic and environmental sustainability (Cascini, Gamberi, Mora, Rosano, and Bortolini, 2016; Gasia et al., 2021).

Since refrigerators having grown to become the most essential household appliance consume the most energy, improving the refrigerators' performance and reducing the energy consumption is a vital matter worldwide. There are various approaches to enhance the performance of refrigeration systems covering the improvement of the heat transfer from heat exchangers (Pirvaram, Sadrameli, and Abdolmaleki, 2019). The ongoing improvement of refrigeration equipment is crucial issue requiring manufacturers, scientists, and policymakers to create efficient and sustainable solutions. Moreover, rising demand for these systems and worries about the environmental impacts of their usage are pushing researchers on this topic (Rossi et al., 2021).

Some processed food frequently requires the use of refrigerators or freezers and these result in increased energy consumption for transport and storage during manufacturing, distribution, sales, and consumer usage phase. Thus, all of these stages should be accounted for the life cycle analysis (Lewandowska, Kurczewski, Joachimiak- lechman, and Zabłocki, 2021). Due to the long lifespan, high energy and material consumption of refrigerators, usage phase of high energy-consuming equipment is very significant for determining its sustainability (Gasia et al., 2021). To keep the required cold temperature for the food or other materials, refrigerant is used in refrigerators. The most commonly used refrigerants (e.g. halogenated alkanes and chlorofluorocarbons (CFCs)) have been linked to the destruction of stratospheric ozone and global climate change and increase the awareness of the necessary developments of variety in cooling technologies. Thus, several regulations covering the production and usage of cooling systems have been adopted in recent decades to reduce the GWP of these refrigerants. By this way, enterprises involved in the manufacture of machines and equipment to adopt products to use low impact refrigerants. There was a deadline for decommissioning of hydrofluorocarbons (HFCs) gases used in refrigerator and freezer equipment whose GWP is higher than 2500 and 150 are specified in this rule for 2020 and 2022, respectively (Cascini et al., 2016; Rossi et al., 2021). Furthermore, refrigeration systems must be developed with high efficiency and low energy consumption as a part of energy-related goods to reduce indirect emissions. For this reason, chlorofluorocarbon refrigerants have been phased out with new technologies based on new refrigerants. There are conceivable alternate fluids with varying environmental performances such as methane series, ethane series, ethers, propane, cyclic organic compounds, miscellaneous organic

compounds, nitrogen compounds, inorganic compounds, and unsaturated organic compounds. Minimum eco-design requirements have been established for the commercialization of refrigerator appliances covering electric-main-operated refrigeration systems for food storage and an eco-design framework for energy-related products in EU to improve the energy efficiency and minimize the emission caused by refrigerants. As a result, the current technical challenge in this sector is to identify innovative technologies capable of ensuring excellent performance, low energy consumption, the use of alternative fluids, and generation of hazardous waste with low environmental effect (Rossi et al., 2021). Energy labelling showing the energy efficiency potential serves to emphasize the benefits of energy-efficient equipment and consumers may save around €150 annually on energy expenditures thanks to the new energy labelling and eco-design regulations. Additionally, the EU energy label consistently advances the technical advancement of energy-efficient household equipment, and the new energy labelling guidelines are expected to save energy use by 167 TWh annually, which is equal to Denmark's annual electricity consumption. Environmental advantages also include the elimination of nearly 46 million tons of CO_2 annually as a result of the implementation of new energy labelling and eco-design requirements (Austrian Energy Agency, 2020).

The examination of the entire refrigeration system life cycle shows that the usage phase including the energy consumption and refrigerant fluid consumption as a leakage during its lifespan has a substantial impact on the total environmental impacts and the indirect emissions caused by the refrigerating unit electric energy consumption are greater than those related to refrigerant leakage (Cascini et al., 2016). In the study, it was assumed that the machine and equipment are free of maintenance throughout the lifetime and the maintenance phase falls outside the system limits. Thus, only refrigerant charge and energy consumption are regarded within this time frame (Rossi et al., 2021). While the study conducted by Rossi et al. (2021) investigates changing the R134 refrigerant fluid to the R744 which generates lower direct emissions during the usage and manufacturing phase (Iraldo et al., 2017), analyzes the environmental impacts regarding the durability of the refrigerator. The usage of the R-407F in the low-temperature system results in better environmental performance than R-404A. Retrofitting the R-404A has considerable environmental benefits for the medium-temperature system. Thus, the ideal option between R-410A (having the highest environmental performance, especially with a set point temperature of 0°C and leakage rate of 10 %) and R-407F is determined by the operational set point temperature and leakage rate (Cascini et al., 2016). According to the study conducted by Rossi et al. (2021), the use of natural fluid (R744) instead of a traditional fluid (R134A) has a beneficial impact on all impact categories with a considerable impact on ODP. Using this fluid instead of a traditional one provides reduction in environmental effects in both

materials and manufacturing phase due to creation of the natural refrigerants and the usage phase due to leakage. Yet, there are numerical differences observed while changing the refrigerant from traditional one to natural one. Even though choosing natural refrigerant is one of the most important eco-design acts, there are requirements for technical advancements to prevent refrigerant leakage by reducing vibrations and monitoring pipe wearing and corrosion. Optimizing the piping size, material selection, corrosion allowance, and routing can be considered key eco-design activities to reduce fluid leakage during usage phase having the major impacts. Due to the increased mass of the fluid in vapor phase and a different heat exchanger design, typical machine using R-134A fluid has wider pipe diameters than using R-744 fluid. Adoption of natural refrigerants requires higher operating pressure with a smaller pipe diameter with greater thickness and more powerful compressing mechanism. These technical necessities result in significant variations in environmental effects related to the materials and production phases compared to the traditional ones. Analyzing the whole life cycle, these design activities allow for a considerable decrease in environmental load with natural refrigerant cooling technologies. Furthermore, energy grid with a high share of renewable sources has low environmental impacts throughout usage phase (Rossi et al., 2021).

It is analyzed that the energy consumption regarding the energy mix during the usage phase is the most crucial aspect affecting the environmental performance. If more renewable energy is used to generate electricity, the environmental impacts caused by usage phase are reduced. Thus, improving the national energy mixes has a credible impact on the product strategy to be taken as a priority. Since, the results show that it is better for environmental reasons to export energy-related and durable products abroad to be used in countries with better national energy mixes than worst national energy mixes (Lewandowska et al., 2021).

Recycling impact is fully allocated to the product using recycled materials while the unrecyclable fraction is disposed in landfill. The material's recyclability is obtained and calculated by the average values of the EU data (Rossi et al., 2021). End of life phase of the refrigeration system includes a first phase of remediation for leftover refrigerants collected. While the refrigerator and refrigerant are handled separately after the cleanup, refrigerating unit is disposed of using manual disassembly, hulk shredding, material separation, metal recycling, burning, or landfill disposal for residue procedures. It is estimated that only 70 % of the recovered gas may be regenerated by filtering and distillation due to the loss of fluid properties (Cascini et al., 2016).

Table 2.1. Analysis of the LCA studies for selected household appliances.

Appliances	**Software**	**Method**	**Datasets**	**Scope**	**References**
Dishwasher	Excel	Various methods	Quantis water database Ecoinvent Literature	Cradle- to- grave	(Van Hoof et al., 2013)
	GaBi 4.0	CML Method	GaBi 4 database	Cradle- to- grave (excluding detergent production and use)	(Zhifeng et al., 2012)
	SimaPro 7.1	CML Method	Primary data Ecoinvent	Gate-to-grave	(Johansson and Björklund, 2010)
Washing Machine	GaBi 6.0	CML Method	Primary data (manufacturer and recycling enterprises) Literature Ecoinvent PE	Cradle-to-grave	(Yuan et al., 2016)
	-	ISO14067	Literature	Cradle-to-grave	(Spreafico and Russo, 2020)
	Open LCA 1.10.3	CML Method	Ecoinvent v3.4 Literature Primary data (manufacturer)	Gate-to-gate	(Sigüenza et al., 2021)
Refrigerator	SimaPro 7.3.3	ILCD 2011	Ecoinvent 2.2 Primary data (manufacturer)	Cradle-to-grave	(Iraldo et al., 2017)
	SimaPro 8.05.13	ReCiPe Method	Ecoinvent v3.1	Cradle-to-grave	(Rossi et al., 2021)
	GaBi 6.0	CML Method	Primary data (manufacturer and disposal enterprises)	Cradle-to-grave	(Xiao, Zhang, Liu, and Yuan, 2015)
	SimaPro 9.1	ReCiPe Method	Ecoinvent 3.6	Cradle-to-grave	(Lewandowska et al., 2021)
	SimaPro	ReCiPe Method	On-site data Ecoinvent v3.1	Cradle-to-grave	(Luglietti et al., 2017)

Table 2.2. Previous LCA data for selected household appliances.

Type of Appliances	Lifetime	Annual Consumption (Unit Per Person)	Uses Per Year Per Person	Uses Per Year	References
Dishwasher	12.5	0.0132	-	-	(Hischier, Reale, Castellani, and Sala, 2020)
	-	-	280	-	(Spreafico and Russo, 2020)
Washing Machine	12.5	0.0296	-	-	(Hischier et al., 2020)
	10	-	-	-	(Yuan et al., 2016)
	-	-	220	-	(European Commission, 2010)
	-	-	-	80.6 (IT) 85.5 (DE) 72.8 (FR)	(Spreafico and Russo, 2020)
Refrigerator	15	0.0222	-	-	(Hischier et al., 2020)

2.5. Relevant EU Documents for This Study

The documents covering the new and updated regulations released by EU themself does not directly set targets for the entire life cycle of dishwashers, washing machines, and refrigerators, but they set several ambitious targets related to energy efficiency, circular economy, and diversifying the energy sources across their life cycle. EU Green Deal is the commitment to cope with climate change and environmental-related burdens as a new strategy to make EU as a prosperous society, resource-efficient, and having competitive economy. By this way, it is aimed that there are no net GHG emissions in 2050 and economic growth is decoupled from resource use regarding the transition in all sectors including the household appliances sector. It is known that the environmental goals of the Green Deal cannot be met by acting alone for Europe since the causes of biodiversity loss and climate change are problems worldwide and cross-national boundaries. Thus, EU can promote its neighbors and stakeholders to join this sustainability boosting applications and driving forces through policies and measures needed to achieve Green Deal's goals which also comply with SDGs by also trade policy. Decarbonization in the energy system is critical to achieve climate targets in 2030 and 2050 because energy production and use across economic sectors account for more than 75 % of the GHG emissions of EU. It should be prioritized to increase energy efficiency and then developing renewable sources. Accelerating the sustainable development of the EU can also be achieved by promoting recycling where only 12 % of the materials come from and circular economy for sustainable products as increasing the reduction of material use by reuse through the extended producer responsibility. Another supportive action is that improving the industry transition of EU through a sustainable model of inclusive growth. Within this strategy, EU will improve the requirements to ensure that all

packaging in EU market is reusable or recyclable by 2030. Other aspects of the EU Green Deal emphasize are to increase the repairability of the appliances and to create toxic-free environment to inhibit pollution into air, water, and soil. The breakthrough innovation and new technologies for sustainable solutions are the key advantage in achieving these targets and it will be supported economically by EU within the Green Deal (European Commission, 2019).

The EU "Fit for 55" has set high goals covering cutting net emissions by at least 55 % by 2030 compared to 1990 and being the first climate neutral continent by 2050. To achieve these goals, it has been planned to ensure fair, competitive, and green transition by 2030 and beyond while strengthening the existing pieces of legislation and presenting new initiatives related to various policy areas and economic sectors such as climate, energy, and fuels. These actions have impact not only on EU but also beyond EU borders while boosting innovation in the products and technologies of the future. The document proposes a revision of the energy efficiency-related regulation to set stricter energy efficiency requirements for household appliances and to decrease the electricity consumption during their use phase. Furthermore, the document mentions the need to improve circularity of the appliances by increasing their repairability, waste management, and use of recycled materials in production (European Commission, 2021).

Within the scope of the EU Green Deal, proposal for Eco-design for Sustainable Products Directive was released to achieve more environmentally sustainable products for almost all physical goods placed on the EU market. The proposal has set various product requirements covering durability, reliability, reusability, repairability, energy and resource efficiency, recycled content, remanufacturing, recycling, environmental footprints, information requirements covering Digital Product Passport which gives digital information about the product material, component, repairability, maintenance to the relevant stakeholders (European Commission, 2022e). Digital Product Passport enhances the shift towards circular economy by promoting material and energy efficiency, prolonging product lifespans, and optimizing product design, manufacturing, use, and disposal phases. By enabling better data access, it promotes new business prospects including product-as-a-service models and enhanced repair, remanufacturing, and recycling. Thanks to this, it also helps consumers to make sustainable decisions and makes it possible for authorities to confirm legal compliance (European Commission, 2023c). This practice also supports the consumer knowledge about the environmental impacts of the products when household appliances are covered within the scope.

EU Energy Labelling and Eco-design Legislation covering the dishwasher, washing machines and refrigerator focuses on the energy efficiency of products in European Market and provides minimum criteria across the EU to decrease poorly performing appliances from the market. This guarantees that customers have access to only appliances that fulfill specific energy efficiency requirements. Furthermore, energy labels on items provide a direct and clear indicator of their energy efficiency and other important qualities to consumers and by this way consumers may be part of the GHG emission reduction by purchasing more energy-efficient equipment. By 2030, this EU regulation is expected to save around 230 million tonnes of oil equivalent (MTOE) and this means that consumers might save up to €285 per year on their energy bills from household consumption. The new EU energy labelling and eco-design regulation is advanced and simplifies the labels by adopting classes from A (most efficient) to G (least efficient) by replacing the previous A+++ to D scale. By this change, it was aimed to enhance consumer clarity by making it easier to identify between energy-efficient appliances and to encourage manufacturers to continue innovating energy-efficient solutions (European Commission, n.d.).

As a building block of the EU Green Deal, the European Commission adopted the Circular Economy Action Plan in March 2020 to promote circular economy for conserving natural resources and creating sustainable growth through the entire life cycle of products while regarding from design phase to end of life phase. It aims to encourage sustainable consumption, waste prevention, and keeping the resources in the EU economy as long as possible due to 70 % increase in waste generation regarding the projection. Within the scope of the action plan, the European Commission drafts legislation to develop sustainability principles and standards that will also address issues such as energy and resource efficiency, toxic chemicals, ban on the destruction of unsold durable goods, rewarding products based on their various sustainability performance, supporting the sustainable and circular bio-based sector, and product durability. Emphasizing on combating single-use and early aging products, the measures cover improving remanufacturing and repairability, lowering environmental footprints and packaging waste, setting minimum requirements for sustainability labels, and increasing recycled content. Thus, this document is fully related to the dishwasher, washing machine, and refrigerator (European Commission, 2020a).

European Commission is implementing its REPowerEU Plan to address the challenges in the world energy market resulting from Russia's invasion of Ukraine. The plan promotes EU to save energy, generate clean energy, and diversify its energy supplies. As mentioned in the plan, medium-term measures to be completed before 2027, relevant to the selected household appliances, are

increasing the investment on sustainable energy management applications, raising the target of EU-wide on energy savings for 2030 from 9 % to 13 %, increasing the renewables target of the EU for 2030 from 40 % to 45 %, and ensuring the access to critical raw materials (European Commission, 2022d).

Since there might be a supply problem for the critical raw materials, EU has published the EU Critical Raw Material Act. Large household appliances contain components including critical raw material. In refrigeration equipment which has compressor components including Nd and Dy; in washing equipment and dishwasher having electric motors and electronics may include Nd, Dy, Pd, Ta, Ru, Ga, Ge, In, Sb (Bacher, Mroueh, and Rietveld, 2013). Because of critical raw materials' limited availability, they carry a vital risk on supply interruption for EU and there is a lack of suitable and reasonably priced replacements by EU Critical Raw Material Act. Thus, this legislation intends to expand and diversify the vital raw material supply for the EU, to make circular practices such as recycling stronger, and to encourage resource efficiency research and innovation as well as the creation of alternatives. By 2030, the Regulation aims to diversify EU supply and establish criteria for local capacity for the supply chain of strategic raw materials while stating:

- Not more than 65 % of the EU's yearly consumption at any relevant stage of processing from a single third country,
- Supply method for EU's annual consumption will be obtained minimum of 10 % of the consumption from extraction, 40 % of them from processing, and 15 % of them from recycling (European Commission, 2023a).

Within the scope of "EU right to repair", it was mentioned that 77 % of Europeans believe that taking action to slow down climate change is their personal responsibility. Even though discarded products are frequently usable items which might be fixed, they are thrown away too soon while resulting in the production of 35 million tons of garbage, 30 million tons of resources, and 261 million tons of GHG emissions annually in EU. According to the projections, choosing replacements over repair costs customers about $12 billion annually. As a part of the plan to make EU carbon neutral by 2050, European Commission has proposed the right-to-repair initiative to seek addressing issues about inconvenience, lack of transparency, or challenging access to repair services. Promoting the repair aims to encourage sustainable consumption and support the environmental goals in EU Green Deal, Circular Economy Action Plan. By this way, saving the money for the customer side and supporting the waste reduction holistically. This proposal suggests repairability standards for a range

of items and upcoming advancements under Union legal acts. To offer important factors for evaluating repair services and to help consumers make more informed decisions, standardized European Repair Information Form is proposed within the scope of right-to-repair. An example of standardized format ought to be given in this directive and this standardized format showing the repair services should give consumers to assess, compare, and give information about repair services. Furthermore, the proposal for a Directive on Empowering Consumers for the Green Transition calls for improved information at the point of sale about durability and repairability of items. This helps consumers to make long-term sustainable purchase decisions. Despite being legally entitled to free repair of damaged items for at least two years, consumers mostly choose replacement due to poor repair alternatives and a legal environment favoring it. The EU puts pressure for change to this wastefulness and amended Sale of Goods Directive requiring repair platforms and technical repairability criteria for individual items as well as prioritizing repair over replacement where costs are equivalent or greater. By this way, it is intended to make customers to select repair, so increasing sustainability and avoiding unnecessary product discarding (European Commission, 2023d).

The EU New Consumer Agenda seeks to allow consumers to make informed decisions while encouraging sustainable consumption. This involves also promoting the manufacture and use of long-lasting, repairable equipment for some products that may cover washing machines, dishwashers, and refrigerators. One of the key concerns about this Agenda is that there is a limited repair option due to lack of access to spare parts and repair services. The initiatives include that making sustainable products by setting product sustainability principles covering durability, repairability, and recyclability, ensuring the electronic devices designed for repair and having software updates, promoting reusable and recyclable packaging to decrease waste, and providing effective tools for consumers to choose sustainable products and repair options (European Commission, 2020b).

The latest version of the new Directive on EU Energy Efficiency which was published in September 20, 2023 covers the ambitious energy efficiency targets regarding the Fit for 55 Package and REPowerEU Plan. The Directive mentions the principle of “energy efficiency first” and EU countries are obliged to consider energy efficiency solutions in all policy regulation, planning, and major investment decisions in energy and non-energy sectors having an impact on energy consumption. Member States will initially appoint one or more bodies to assess whether the energy efficiency concept is being followed or not. According to the Directive, EU countries will develop and transparently share cost-benefit methodologies covering societal issues such as decreasing GHG emissions, and improving people’s well-being and energy independence. By this way, the EU nations

will achieve 17.7 % decrease in final and primary energy use by 2030 compared to the 2020 baseline scenario predictions while increasing annual energy savings from the present value 0.8 to 1.49 % of new annual savings for the 2024-2030 time period (European Commission, 2023b).

The European Commission proposed two new regulations about the Phase Down Fluorinated Greenhouse Gases and Ozone Depleting Substances to tighten controls on F-gases and ozone-depleting substances (ODS) for combating climate change. Reduction of emissions by at least 55 % by 2030 will be contributed by bringing these proposals into action and having target to save 40 million tons of CO_2 equivalent emissions by 2030 with strengthened F-gas proposal which plans to reduce potential impact of HFCs on climate change by 98 % through stronger limitations and prohibitions on unnecessary uses, has stricter trader restrictions and enhances monitoring boost enforcement. Within these applications, EU member states will increase training for climate-friendly alternatives and be sure to comply with Montreal Protocol (European Commission, 2022c).

Beyond EU borders, EU policies, technological standards, and testing methods have had a favorable impact. Some EU trade partners and producers in other major exporting nations must follow and align the EU's regulations to reach the EU market. The Customs Union Agreement that Türkiye signed with EU in 1995 states also the implementation of the technical legislation in Türkiye (European Commission, 2022a). Thus, Türkiye trading with EU should follow the above-mentioned regulations and legislation. Furthermore, EU playing a pioneering role in sustainability is considered as a good practice example for Türkiye and other countries in their sustainability journey. Therefore, it is very important to evaluate its practices and integrate them into countries.

3. MATERIALS AND METHODS

In this research, it is aimed to identify environmental hot spots throughout the life cycle of dishwasher, refrigerator, and washing machine. By doing this, the quantitative LCA has been used to effectively evaluate the significant environmental impacts and enables the selection of environmentally optimized solutions. There are 4 main steps for the LCA methodology of this study: (1) goal and scope definition, (2) life cycle inventory analysis, (3) life cycle impact assessment, and (4) interpretation:

- ***Goal and scope definition:*** This study aims to quantify the environmental impacts of three household appliances including refrigerators, washing machines, and dishwashers by comparing the cleaner electricity mix options, durability, and consumer behavior and choices for both product groups in Türkiye. The system boundaries for both appliances start from the raw material extraction to the disposal phase of their life cycle, cradle to grave approach (Figure 3.1). This study will be conducted by using GaBi 8 software and Ecoinvent database was used to characterize materials, energy sources, and other processes. The flows involved in the products were modeled in the Ecoinvent database using "Allocation, cut-off by classification" system model (Rossi et al., 2021). Manufacture phase has also covered the raw material phase in its interior data taken from the database. The method for the analysis of the LCA was selected as CML 2001 midpoint due to the common analysis in the literature as seen in Table 2.1. In the CML 2001 method, following impact categories were evaluated with their own units (Table 3.1). According to the normalization results, the main focus on characterization impacts is analyzed for MAETP, CC, FAETP, HTP, and ADP-Fossil fuels for all selected household appliances. The target audience of this study is domestic appliance manufacturers, consumers, and governments promoting companies to choose more environmentally friendly ways. Within the scope of the study, functional units of the appliances are 1 domestic dishwasher, 1 washing machine, and 1 refrigerator. The weight of dishwasher, washing machine, and refrigerator are 50, 75, and 60 kg, respectively as given in the Ecoinvent database. In this study, it is assumed that these appliances were manufactured in Türkiye in 2022. Even though there were different lifetime defined in the literature, the lifetime of the appliances is assumed as 13 years as a baseline scenario to evaluate them together.

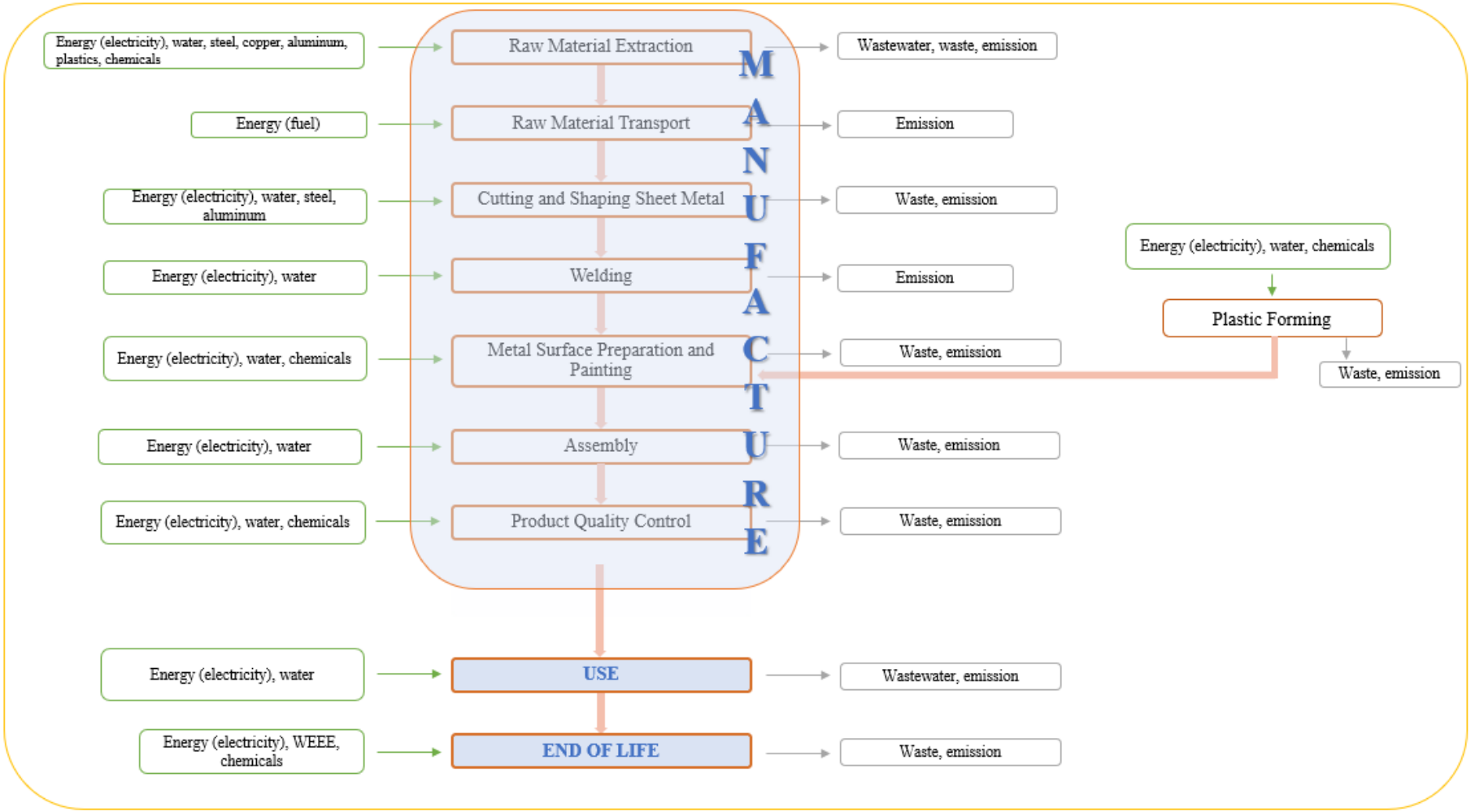

Figure 3.1. System boundaries of selected household appliances (adopted from Turkish Ministry of Environment, Urbanization and Climate Change, 2019).

Table 3.1. Impact categories analyzed in the CML 2001 Method.

Impact Categories	Unit
Acidification	kg SO_2-Eq
Climate change - Global warming potential for 100 years	kg CO_2-Eq
Ecotoxicity: Freshwater aquatic ecotoxicity	kg 1,4-DCB-Eq
Ecotoxicity: Marine aquatic ecotoxicity	kg 1,4-DCB-Eq
Ecotoxicity: Terrestrial ecotoxicity	kg 1,4-DCB-Eq
Energy resources: Abiotic depletion potential: Fossil fuels	MJ
Eutrophication	kg PO4-Eq
Human toxicity	kg 1,4-DCB-Eq
Material resources: Abiotic depletion potential: Elements	kg Sb-Eq
Ozone depletion - Ozone layer depletion	kg CFC-11-Eq
Photochemical oxidant formation	kg ethylene-Eq

- ***Life cycle inventory analysis:*** Data required for this study will be obtained from the literature, Ecoinvent database, relevant statistics, and required assumptions for each household appliances. To assess the data quality, the appropriate geographical location, technology, and time to the feasible maximum degree of the process should be utilized as data. The secondary datasets are used for appropriate location and technology. It is important to predict appropriate energy consumption data during the manufacturing and usage phase in different locations (Lewandowska et al., 2021). While doing this research, selected documents were conducted through Google Scholar database by searching LCA of washing machine, refrigerator, and dishwasher. The references used while calculating the LCA of selected household appliances are given in Table 3.2. There was lack of detergent data for dishwasher and it was found in the literature for washing machine. Detergent might also be used in refrigerator for cleaning purposes. To evaluate all selected appliances in the same bases, detergent, and packaging are not included. For the raw material extraction phase assumptions, Ecoinvent database is used to evaluate as the same with all selected appliances and it is shown in the manufacturing phase. Since the transportation phase does have impact less than 5 %, it is excluded in this study (Zhifeng et al., 2012; Yuan et al., 2016). Building halls for the end of life phase were excluded due to lack of data for all appliances and the manufacturing phases have their data for building hall in Ecoinvent to be used. For the refrigerator, HFC-152a is given as refrigerant in

Ecoinvent and it is assumed that there is no refrigerant leakage during manufacture phase of the refrigerator.

Table 3.2. Data references of all selected appliances in their life cycle.

Appliances	Life Cycle Stage	References
Dishwasher	Manufacture	Ecoinvent
	Use	(Ardente and Talens Peiró, 2015)
	End of Life	(Ardente and Talens Peiró, 2015; Xiao et al., 2015)
Washing Machine	Manufacture	Ecoinvent
	Use	(Sigüenza et al., 2021; Xiao et al., 2015)
	End of Life	
Refrigerator	Manufacture	Ecoinvent
	Use	(Xiao et al., 2015)
	End of Life	(Sigüenza et al., 2021; Xiao et al., 2015)

Electricity

To achieve the most correct data as in reality the selected energy sources are classified and calculated by using the generation of the electricity mix given in the 2022 Energy Balance Table for Türkiye (Ministry of Energy and Natural Resources, 2023a). This calculation is more or less the same with the announcement of the MENR and is taken as a baseline for the calculations in the 2035 scenario. In other words, electricity data for 2022 has been evaluated to make better predictions and calculations for the 2035 scenario and to analyze the data given in the database (Ecoinvent). While calculating the electricity generation given in Table 3.3, there were some assumptions to integrate the data while using GaBi. The assumptions made for this study are as follows:

- Türkiye generates its electricity without any electricity import and export.
- There is no transmission and distribution loss while obtaining the electricity for 2022 and 2035 scenarios.
- The transmission lines are included for both scenarios as defined in Ecoinvent version.
- SF_6 emission has been considered while analyzing electricity in all scenarios as defined in Ecoinvent version.

- Asphaltite and petroleum consumption to generate electricity are taken as lignite due to the lack of data about the fossil fuel consumption for electricity mix for 2035 to make the data in the same ground for 2022 and 2035.
- Since there is limited data for the 2035 scenario in the National Energy Plan, it was assumed that hard coal and lignite correspond the same percentage as 50 % for the electricity generation.
- For the 2035 scenario given in the National Energy Plan, geothermal and other (biowaste and energy) sources of electricity are given together and it was assumed that both correspond the same percentage as 50 % for the electricity generation.
- For the up to 2053 scenarios (S4 and S5), the electricity mix is taken as the same with 2035 scenario.

Table 3.3. Electricity generation estimations adopted and calculated from the 2022 Türkiye Energy Balance Table (Ministry of Energy and Natural Resources, 2023a) and National Energy Plan (Ministry of Energy and Natural Resources, 2023b).

Electricity Resources	**2022 Adopted (kWh)**	**2035 Assumed in This Study (kWh)**	**2035 National Energy Plan (kWh)**
Hard Coal	0.195	0.077	0.342
Lignite	0.145	0.077	
Natural Gas	0.221	0.187	
Hydro	0.197	0.173	0.173
Wind	0.103	0.177	0.177
Solar	0.050	0.165	0.165
Geothermal	0.033	0.016	0.032
Other (bioenergy and waste)	0.056	0.016	
Nuclear	-	0.111	0.111
Total	1	1	1

End of Life

End of life phase for the study has been implemented with a lack of data as mentioned in the literature review part. Thus, there are some assumptions made for all appliances to deal with this problem. Even though there are many materials might be recycled in the inventory table, only aluminium, steel, copper, and PVC are recycled as given percentage in Table 3.4, and all of the other

waste is incinerated and landfilled as assumptions. For the dishwasher, it was assumed that used cable, printed wiring boards, and waste concrete are hazardous, waste rubber, and wood are non-hazardous. For the refrigerator, epoxy resin was assumed as PVC in Ecoinvent database.

Table 3.4. End of life assumptions and amount for all selected household appliances.

					Waste Management Percentage (%) (Sigüenza et al., 2021)		
Waste Material	**Dishwasher**	**Washing Machine**	**Refrigerator**	**Unit**	**Recycling**	**Landfill**	**Incineration**
Aluminium	0.400	5.760	2.189	kg	0.95	0.05	
Steel	34.200	32.020	32.093	kg	0.95	0.05	
Copper	0.850	1.810	1.308	kg	0.95	0.05	
PVC	6.300	1.020	0.578	kg	0.30	0.30	0.40
Other-non-hazardous	5.730	32.330	29.886	kg	-	-	1
Other-hazardous	2.200	1.350	0.240	kg	-	-	1

- ***Life cycle impact assessment:*** Evaluation of the data will be focused on analyzing all environmental impact categories in the CML 2001 method while conducting the characterization and normalization. It has been assumed that the selected household appliances manufactured at the beginning of 2022 have been started to be used in the same year.

Covering the consumption behavior and choice, durability, and electricity, eight scenarios focusing on the usage stage and electricity consumption for Türkiye have been analyzed in this study. The explanation for the scenarios is given as follows:

Scenario 1 (S1) - Türkiye 2022 Electricity Mix: Electricity consumption is taken and calculated from the 2022 Energy Balance Table (Ministry of Energy and Natural Resources, 2023a) for the manufacture, use, and end of life stages with a 13 years lifetime for all selected household appliances. For the water consumption during the use phase of the dishwasher and washing machine, tap water and washing cycle have been considered as 280 and 220 as given in Table 2.2, respectively.

Scenario 2 (S2) - Türkiye 2035 Electricity Mix: Electricity consumption is considered and calculated from the Türkiye National Energy Plan (Ministry of Energy and Natural Resources, 2023b) for the manufacture, use and end of life stages with a 13 years lifetime for all selected household appliances. For the water consumption during the use phase of the dishwasher and washing machine,

tap water and washing cycle have been considered as 280 and 220, respectively. This scenario is considered as a baseline scenario and is compared with the other scenarios to evaluate the impact change.

Scenario 3 (S3) - Normal Lifetime (13) up to 2053: This scenario is analyzed to evaluate the durability of the selected household appliances up to 2053 when the time Türkiye has planned to achieve net zero emission. Lifetime of the household appliances is considered as 13 years without any lifetime extension and it is assumed that there will be 3 household appliances will be used from 2022 to 2053. Thus, 3 household appliances will be manufactured and 2 of them will be disposed in this time frame. In this scenario 2035 electricity mix estimation is used for electricity consumption during manufacturing, use, and end of life phase. For the water consumption during the use phase of the dishwasher and washing machine, tap water and washing cycle have been considered as 280 and 220, respectively. In this scenario, the replacement of the same machine is assumed without changing the technological advancement and energy efficiency.

Scenario 4 (S4) – Extended Lifetime (20) up to 2053: To evaluate the durability of the selected household appliances up to 2053, it was assessed that 2 selected household appliances are manufactured, used and one of them is disposed from 2022 to 2053. The first household appliances are used for 20 years and the other one will be used for 11 years. In this scenario 2035 electricity mix estimation is used for electricity consumption during manufacturing, use, and end of life phase. For the water consumption during the use phase of the dishwasher and washing machine, tap water and washing cycle have been considered as 280 and 220, respectively. In this scenario, the replacement of the same machine is assumed without changing the technological advancement and energy efficiency.

Scenario 5 (S5) – Normal Lifetime (13) up to 2053 and Renewing Appliances With 20 % More Energy-Efficient Ones: This scenario is the same with Scenario 3 except for the assumption covering the change of the oldest appliances with the newest one having 20 % more energy-efficient feature. In this scenario the first appliances will be used for 13 years as the same appliances as Scenario 2, the second appliances will be used for 18 (13+5) years with 20 % more efficient ones. Thus, 3 appliances are manufactured, used and two of them are sent to the end of life phase. Household appliances have 25 % potential of electricity saving in the maximum efficiency scenario based on the newly developed technologies (Yilmaz et al., 2019). For the sake of pointing out, it is assumed that 20 % increase in energy efficiency is considered in this study.

Scenario 6 (S6) – 20 % More Energy-Efficient Appliance in Use Phase: Analysis of the electricity consumption and consumer choice about the energy-efficient ones during use phase is implemented by decreasing the 20 % electricity consumption of the selected household appliances analyzed in the baseline scenario with 2035 Türkiye's electricity mix and lifetime of 13 years.

Scenario 7 (S7) – 20 % Reduction in Washing Cycle in Use Phase: Analysis of the consumer behavior about the washing cycles for dishwasher and washing machine is implemented by reducing the washing cycle in 20 % in a year with 2035 Türkiye's electricity mix and lifetime of 13 years. This scenario is not applicable for refrigerator. This scenario might be considered as pay per-wash circular economy model implemented the study conducted by Sigüenza et al. (2021).

Scenario 8 (S8) – 20 % More Energy-Efficient Appliance and 20 % Reduction in Washing Cycle in Use Phase: Analysis of the consumer behavior and choice about the washing cycles and preferring the energy-efficient appliances for dishwasher and washing machine is implemented by reducing the washing cycle in 20 % in a year and decreasing the electricity consumption as 20 % in use phase with 2035 Türkiye's electricity mix and lifetime of 13 years.

- ***Interpretation:*** Results of the study will be used for determination of the environmental hotspots throughout the raw material selection, manufacturing, service, and end of life stage of each household appliance and will give information about the lifecycle stage which requires the circular economy solutions the most. Thus, it will guide about the most environmentally friendly appliance groups covering the change in the environmental impacts for different consumer behaviors and electricity mix.

4. RESULTS AND DISCUSSION

Evaluation of the selected household appliances which are dishwasher, washing machine, and refrigerator has been implemented within this study via LCA, and the results are obtained by using the literature, software, database, and CML method. Within the scope of the study, the evaluated scenarios each provide a distinct route to environmental sustainability, highlighting the significance of consumer behavior and choice, cleaner electricity mix, product longevity, energy efficiency, and technology improvements in minimizing negative effects on the environment by being aware of the most impactful categories for each selected appliance. Furthermore, a comparison of the impact of these circular economy pillars shows each impact category's relative benefits has been carried out in order to determine which are the most significant for each.

In this study, normalization was conducted for the S1 (electricity mix in 2022) to examine the environmental impacts at the date closest to the present day and to identify the top 5 impact categories with the highest impacts. Normalization results of all selected household appliances show that CC, FAETP, MAETP, ADP-Fossil fuel, and HTP impact categories have the highest load in the environment. Thus, these impact categories have been analyzed in depth while evaluating all scenarios for selected household appliances.

4.1. LCA Results of Dishwasher

Evaluating the LCA of the dishwasher proves that the use phase is the most impactful life cycle stage (Binstock et al., 2013; Van Hoof et al., 2013; Zhifeng et al., 2012). Also, in this study, use phase of the dishwasher is mostly the highest impact on the life cycle for almost all impact categories excluding ADP-Materials as given in Figure 4.1 for the first scenario. As mentioned in the study conducted by Zhifeng et al. (2012), it is important to support consumers about changing their behavior during use phase to reduce electricity, water consumption, and the most serious impact among the impact categories is MAETP and the second one is CC due to the thermal power plants. This also complies with this study because of having the highest impact category in MAETP and CC, respectively when compared to other categories.

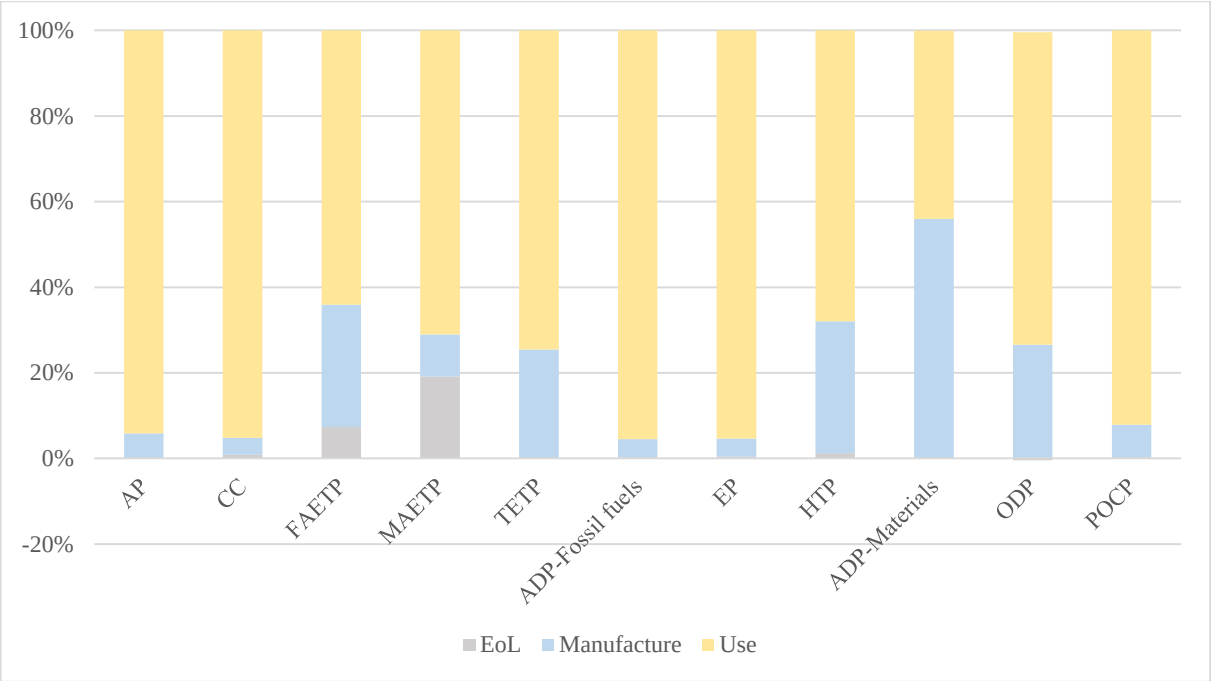

Figure 4.1. Impact ratio in the total lifecycle according to the characterization results of the dishwasher in Türkiye 2022 electricity mix scenario (S1).

ADP-Materials impact factor due to the raw material consumption during the manufacturing phase including the raw material extraction together is higher when compared to the other impact categories. 56% of the total impact of ADP-Materials has been caused by manufacturing phase due to using the printed wiring board, copper, and cable having impact of 38.90 %, 31.56 %, and 21.66 %, respectively. More than 95 % of the ADP-Materials impact caused by the printed wiring board has been responsible for the gold mine operation and production. In the end of life phase of the dishwasher, there has been a minus impact for ADP-Materials and ODP due to the recycling of the PVC and metal scrap. For the other impact categories, use phase has the highest load due to electricity consumption from fossil fuels, especially from lignite and hard coal. Use phase impact for CC, FAETP, MAETP, ADP-Fossil fuel, and HTP categories correspond to the 95.19 %, 64.09 %, 71.05 %, 95.51 %, and 67.98 % in their total life cycle impact, respectively. As mentioned in the study conducted by Binstock et al. (2013), these impacts might vary depending on the pre-rinsing behavior, washing temperature, water consumption, and detergent usage amount.

Considering the causes of these impact categories in the whole life cycle impact are analyzed as follows for the first scenario of dishwasher while mentioning the highest impacted processes:

- CC: 32.31 %, 31.02 % and 10.69 % of the climate change impact have caused by the electricity production from lignite, hard coal, and natural gas from conventional power plant, respectively. These impacts are dominant in use phase and have direct impact on the cumulative results.
- FAETP: 28.54 %, 7.81 %, and 15.40 % of the freshwater ecotoxicity impact have caused by the treatment of spoil from lignite mining and hard coal mining and treatment of scrap copper by municipal incineration, respectively.
- MAETP: 26.44 %, 19.01 %, and 14.19 % of marine ecotoxicity impact have caused by the treatment of spoil from lignite mining, treatment of solid waste by incineration, and electricity production from hard coal, respectively.
- ADP-Fossil fuel: 28.01 %, 21.43 %, and 8.22 % of abiotic depletion from fossil fuel impact have caused by the electricity production processes covering lignite and hard coal operation and preparation and natural gas production, respectively.
- HTP: 14.93 %, 14.35 %, and 7.11 % of human toxicity impact have caused by the treatment of spoil from lignite mining to be used as electricity in all phases, smelting of copper concentrate, and treatment of sulfidic tailings from copper mine operations, respectively.

4.1.1. Clean energy mix comparison (S1 and S2)

When comparing Türkiye's 2035 electricity mix (S2) to the 2022 mix (S1), the environmental effect of dishwashers decreases noticeably in all categories. The impact change for the total lifecycle due to 2035 cleaner energy mix results in a 19.30 % reduction in the impact of CC and 17.93 % decrease in the ADP-Fossil fuels. Further evidence of the future energy mix's wide environmental advantages comes from the decreases in FAETP by 8.08 %, MAETP by 14.56 %, and HTP by 6.81 %. As seen in Figure 4.2, most of the changes are seen in use phase as more than 10 % impact reduction in all impact categories excluding the ADP-Fossil fuel in end of life phase by 20.85 % decrease in impact due to less lignite and hard coal mine operation and preparation required in 2035 electricity mix. These results are in line with the study mentioning the environmental gains through cleaner electricity mix (Hischier et al., 2020).

Considering the causes of these impact categories in cumulative life cycle impact are analyzed as follows for the clean electricity mix scenarios for 2022 and 2035 in Türkiye comparison of dishwasher (S1 and S2):

- CC: There are 19.84 %, 27.93 %, and 13.91 % impact reductions caused by the electricity production from lignite, hard coal, and natural gas from conventional power plant, respectively.
- FAETP: Lowering the freshwater ecotoxicity impact is caused by the 19.12 % and 26.34 % impact reduction in treatment of spoil from lignite mining and the treatment of spoil from hard coal mining in Türkiye.
- MAETP: There is 19.34 %, 27.89 %, and 26.46 % impact reduction in treatment of spoil from lignite mining, electricity production from hard coal and the treatment of spoil from hard coal mining led to alleviate the marine ecotoxicity thanks to cleaner electricity mix in 2035.
- ADP-Fossil fuel: Impact reduction is seen in this impact category due to 19.83 % and 27.55 % impact mitigation caused by the decrease in lignite mine operation and hard coal mine operation and preparation indicating a reduced dependency on fossil fuels, respectively.
- HTP: 19.48 % impact reduction caused by the treatment of spoil from lignite mining causes less human toxicity potential.

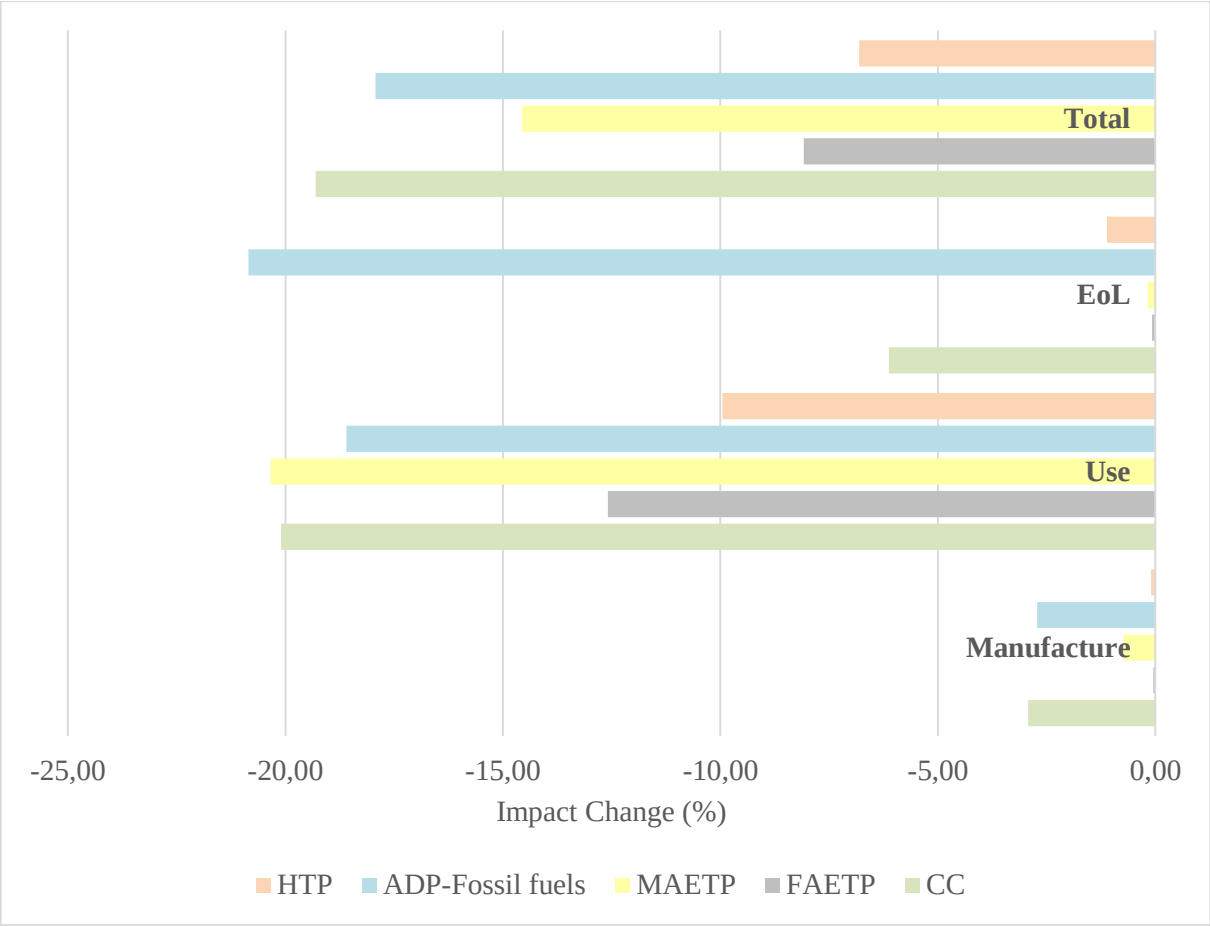

Figure 4.2. Change in characterization results for 2035 electricity mix compared to 2022 electricity mix of the dishwasher for each life cycle phases in Türkiye (%).

4.1.2. Durability comparison up to 2053 (S3, S4, and S5)

As seen in Figure 4.3, the weights of different impact categories in each scenario change with different life cycle phases. To illustrate, the CC effect was 93.26 %, 95.54 %, and 92.45 %; FAETP effect was 57.12 %, 67.48 %, and 54.10 %; MAETP effect was 66.7 0%, 77.79 %, and 63.92 %; ADP-Fossil fuels effect was 93.56 %, 95.65 %, and 92.78 %; HTP effect was 60.65 %, 69.95 %, and 57.76 % for the use phase of S3, S4, and S5, respectively. In this case, the impacts of S3 and S5 scenarios in the manufacturing and disposal stages have increased. This is because more appliances were manufactured and disposed in scenarios S3 and S5 compared to scenario S4.

When dishwashers with longer lifespans (S4) are compared to those with shorter lifespans (S3), the effects of CC is reduced by 2.39 % due to low electricity production from lignite, hard coal, and natural gas, ADP-Fossil fuels are reduced by 2.18 % due to low lignite, hard coal mine operation, and preparation, FAETP is reduced by 15.35 % due to low treatment of scrap copper, MAETP is reduced

by 14.26 % due to low electricity consumption from hard coal in manufacture and disposal phase, and HTP is reduced by 13.29 % due to low smelting of copper concentrate and treatment of sulfidic tailings from copper mine operation in total lifecycle impact as seen in Figure 4.3. These numbers indicate that improving product durability can result in reasonable environmental savings for some impact categories as mentioned in the study conducted by Iraldo et al. (2017). The reason of these impacts is caused due to more manufacturing, and disposal are required for no extension of the lifetime scenario (S4). When the lifetime extension of the dishwasher as of 20 years, the end of life and manufacture impacts in all impact categories can be decreased by 50 % and 33.33 %, consecutively. No change in the use phase ever occurred because it was assumed that the dishwasher would be renewed with the same appliance.

If more energy-efficient appliances are used while replacing with the newest and energy-efficient ones, the environmental impacts will change considerably in some impact categories as stated in the study performed by Horie (2004). Considering the causes of these impact categories in cumulative life cycle impact are analyzed as follows for the comparison of dishwasher for S5 with S3 and S4:

- CC: If renewing the dishwasher when it reaches its lifetime scenario realized up to 2053 (S5), there is 10.73 % and 8.55 % impact reduction compared to the S3 and S4, respectively. These impact reductions are observed due to the low electricity production and consumption from hard coal and lignite in use phase.
- FAETP: While lowering the freshwater ecotoxicity impact in S5 is caused by the 6.59 % impact reduction in treatment of spoil from lignite mining when compared to the S3, there is impact increase in S5 compared to S4 as 10.35 % due to the treatment of scrap copper and requiring more manufacture and disposal phase for more appliances used in S5.
- MAETP: While decreasing the marine ecotoxicity impact in S5 is caused by the 7.70 % impact reduction in treatment of spoil from lignite mining when compared to the S3, there is impact increase in S5 compared to S4 as 7.65 % due to the treatment of municipal waste with incineration and scrap copper and requiring more manufacture and disposal phase for more appliances used in S5.
- ADP-Fossil fuel: Renewing the dishwasher when it reaches its lifetime scenario realized up to 2053 results in 10.78 % and 8.79 % impact reduction compared to the S3 and S4, respectively. These impact reductions are observed due to the low electricity production and consumption from hard coal and lignite in use phase even though more manufacture and disposal is required for S5.

- HTP: While decreasing human toxicity impact in S5 is caused by the 6.86 % impact reduction in treatment of spoil from lignite mining and electricity production from hard coal when compared to the S3, there is impact increase in S5 compared to S4 as 7.42 % due to the smelting of copper concentrate and treatment of sulfidic tailings from copper mine operations in S5.

To sum up, if it is desired to decrease only CC and ADP-Fossil fuel impact, the best scenario is S5; if it is desired to decrease the all CC, FAETP, MAETP, ADP-Fossil fuel, and HTP impact without harming any impact areas, the best scenario is S4.

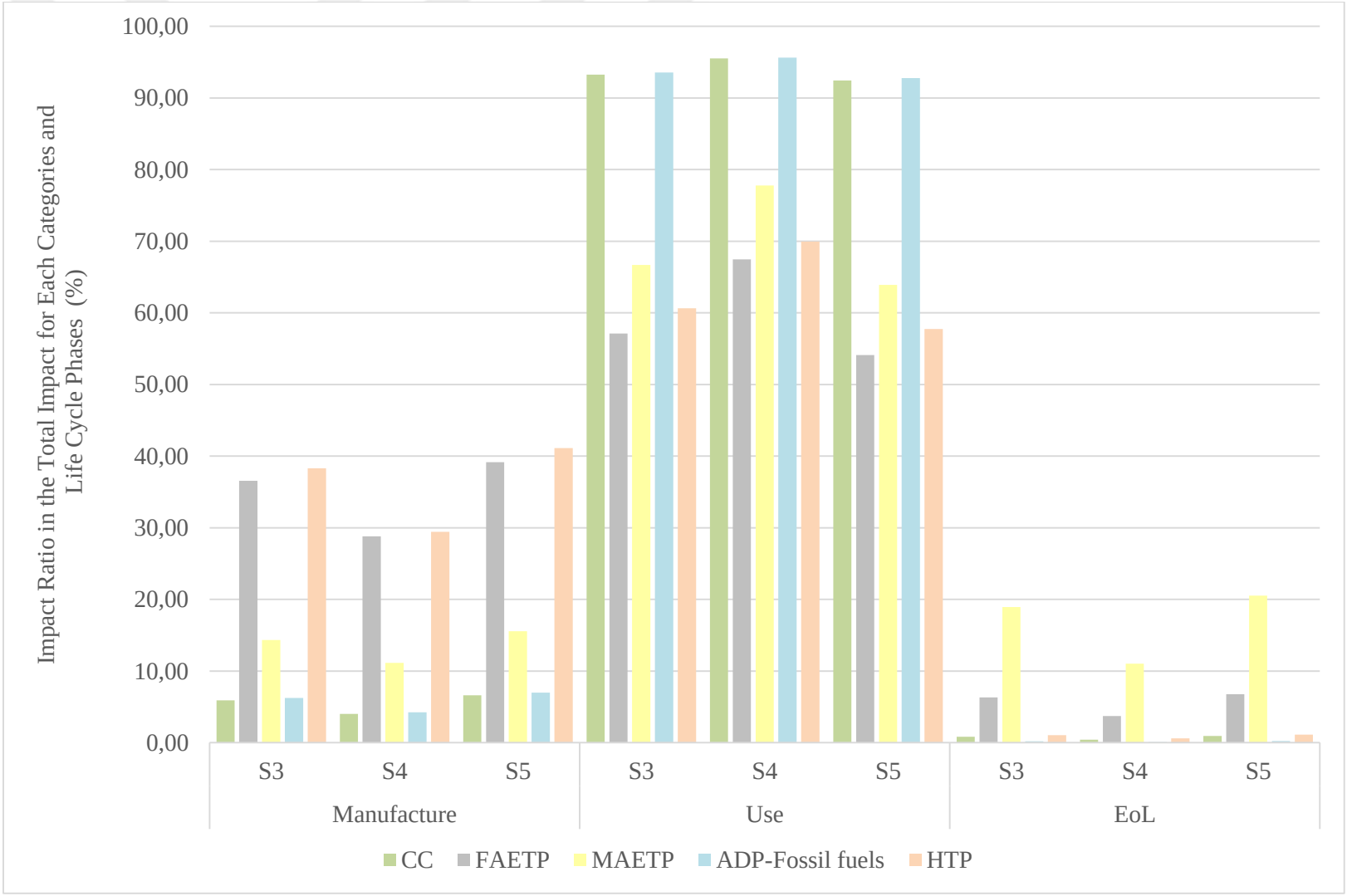

Figure 4.3. Change in characterization results of the dishwasher for durability scenario up to 2053 for S3, S4, and S5 (where, S3: Normal lifetime (13) up to 2053, S4: Extended lifetime (20) up to 2053, S5: Normal lifetime (13) up to 2053 and renewing the appliances with 20 % more energy-efficient ones).

4.1.3. Consumer choice comparison (S2 and S6)

Implementing a 20 % increase in energy efficiency for the dishwasher used in Türkiye (S6) in comparison to the electricity consumption in S2 (less efficient case) results in reductions of use phase around 19.82 %, 19.85 %, 19.89 %, 19.84%, and 19.47 % in CC, ADP-Fossil fuels, FAETP, MAETP, and HTP, respectively. As concluded in the study conducted by Hischier et al. (2020), this study also suggests that energy efficiency in use phase significantly improves environmental impact categories.

Considering the causes of these impact categories in life cycle impact for use phase are analyzed and compared as follows for the use of 20 % more energy-efficient dishwasher in Türkiye (S2 and S6):

- CC: There are 19.90 %, 20 %, and 19.94 % impact reduction caused by the electricity production from lignite, hard coal, and natural gas through conventional power plant, respectively.
- FAETP: Lowering the freshwater ecotoxicity impact is caused by 20.37 %, 20.06 %, and 20.08 % impact reduction in treatment of spoil from lignite mining, treatment of scrap copper through municipal incineration, and treatment of spoil from hard coal mining when using 20% more energy-efficient dishwasher in Türkiye.
- MAETP: 19.72 %, 20.29 %, and 20.04 % impact reduction in treatment of spoil from lignite mining, electricity production from hard coal, and treatment of spoil from hard coal mining led to alleviate the marine ecotoxicity in this scenario comparison.
- ADP-Fossil fuel: Impact reduction is seen in this impact category due to around 20 % impact mitigation caused by the decrease in hard coal and lignite mine operation and preparation.
- HTP: 19.96 % impact reduction caused by the treatment of spoil from lignite mining and around 20 % decrease in impact due to lower electricity production from hard coal, smelting of copper concentrate cause less human toxicity potential when using more energy-efficient dishwasher.

4.1.4. Consumer behavior comparison (S2 and S7)

There is a consistent 20 % drop in all impact categories, including CC, ADP-Fossil fuels, FAETP, MAETP, and HTP, when comparing scenario S7 (20 % washing cycle reduction in usage phase) to S2. This demonstrates how cutting down on washing cycles has a major positive

environmental impact, if possible without compromising the comfort of the consumer. This might be achieved by promoting the use of dishwasher when it is fully loaded. In another word, using a dishwasher 4 times a week as opposed to 5 is almost equivalent to using 20 % more efficient dishwasher while reducing the washing cycle by 20 % in a year. Considering the causes of these impact categories in life cycle impact for use phase are analyzed and compared with the 20 % less washing cycle in use phase of dishwasher in Türkiye (S2 and S7) and the impact reduction reasons are almost the same with the comparison of 20 % more energy-efficient appliances usage (S2 and S6) for CC, FAETP, MAETP, ADP-Fossil fuel, and HTP.

4.1.5. Consumer choice and behavior comparison (S2 and S8)

With a combined 20 % washing cycle reduction and more energy-efficient in usage phase, scenario S8 exhibits the largest reductions when compared to S2, with around 35.40 % less in all impact categories covering CC, FAETP, MAETP, ADP-Fossil fuels, and HTP. This example demonstrates the synergistic impact of lower washing cycles and higher energy efficiency.

Considering the causes of these impact categories in life cycle impact for use phase are analyzed and compared as follows for the more energy-efficient with 20 % less washing cycle usage in dishwasher (S2 and S8):

- CC: Lowering the production of electricity from lignite, hard coal, and natural gas through conventional power plants has an impact decrease of around 35.90 %.
- FAETP: Lowering the freshwater ecotoxicity impact is caused by 36.24 %, 35.92 %, and 35.91 % impact reduction in treatment of spoil from lignite mining, treatment of scrap copper through municipal incineration, and treatment of spoil from hard coal mining.
- MAETP: 35.78 %, 36.19 %, and 35.96 % impact reduction in treatment of spoil from lignite mining, electricity production from hard coal, and treatment of spoil from hard coal mining led to alleviate the marine ecotoxicity.
- ADP-Fossil fuel: Impact reduction is seen in this impact category due to around 36 % impact mitigation caused by the decrease in hard coal and lignite mine operation and preparation.
- HTP: 35.93 % impact reduction caused by the treatment of spoil from lignite mining and around 36 % decrease in impact due to lower electricity production from hard coal, smelting of copper concentrate cause less human toxicity potential.

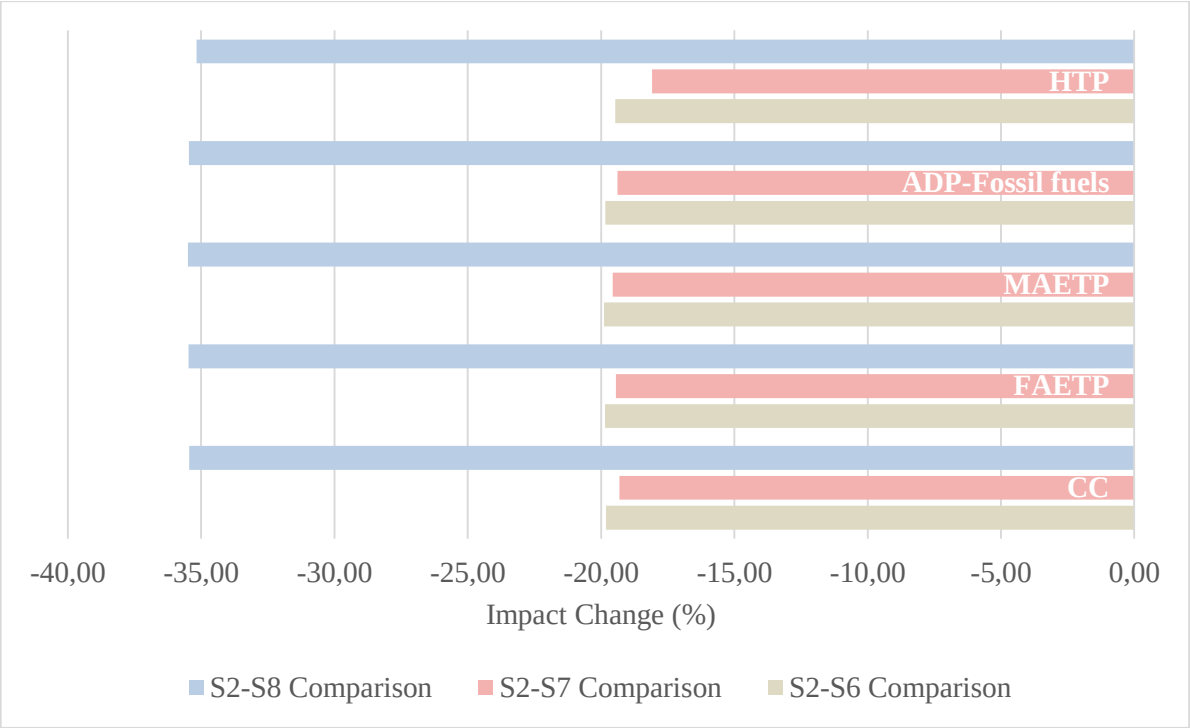

Figure 4.4. Impact change comparison between S2 and S6, S7, and S8 for each impact categories for dishwasher (where, S2: 2035 Electricity mix in Türkiye, S6: 20 % more energy-efficient dishwasher, S7: 20 % of washing cycle reduction, and S8: 20 % more energy-efficient appliance selection and 20 % of washing cycle reduction).

As seen in Figure 4.4, the highest environmental savings can be achieved with the combination of 20 % more energy-efficient with 20 % less washing cycle for dishwasher. Even though only 20 % less washing cycle usage represents less environmental impacts when compared to 20 % more energy-efficient dishwasher usage, there is slight difference between each of these scenarios. As emphasized above, it can be concluded that using a dishwasher 4 times a week as opposed to 5 is almost equivalent to using 20 % more efficient dishwasher while reducing the washing cycle by 20 % in a year.

As mentioned in the literature, future trends are estimated to have benefits regarding both water and energy savings by expanding renewable energy resources and having better water and energy saving tactics and superior environmentally friendly dishwashing designs (Binstock et al., 2013). Even though this study focuses on the use phase of the dishwasher, practical design suggestions for dishwasher help to decrease the environmental impacts in other life cycle stages while it can also enhance the use phase in terms of maintenance and repair of the dishwashers by supporting the EU Right to Repair. These solutions were mentioned to make electrical components, motors, and similar parts to be connected physically to be removed easily. Some dishwashers in current waste stream already have this feature even it was intended for the manufacturing stage, it is beneficial solution for

the disassembly step as well. By this reason, end of life stage of the dishwasher is vital for energy generation not only for the requirement of the less virgin material, but also less energy requirement for the secondary material into new products (Johansson and Björklund, 2010).

4.2. LCA Results of Washing Machine

While Sigüenza et al. (2021) analyzed the benefits of circular business models in mitigating climate change impact are outweighed by the benefits of decarbonized electricity, Yuan et al., (2016) evaluated the LCA of washing machine including detergent usage. Both studies highlighted the environmental impacts of the washing machine are caused mostly by use phase. It is found that use phase with a key cause of environmental burdens as electricity consumption has the highest burden on the environment (Yuan et al., 2016). This indicates that the use phase, particularly electricity use, is a significant contributor and this study gives also insight about the impact change with electricity consumption and circular economy pillars covering the use phase.

As seen in Figure 4.5, use phase of the washing machine has the highest load when compared to other life cycle phases excluding MAETP (54.21 %) impact of end of life phase due to the assumption made for incineration of the waste and treatment of spoil from lignite mining, ADP-Materials (60.67 %) caused mostly by electrorefining of copper and FAETP (38.75 %) due to the treatment of the scrap copper and electrorefining copper in manufacture phases. Use phase carries the biggest burden on the other effect categories because of the electricity usage from fossil fuels in high amounts in their lifetime cumulatively. Use phase impact for CC, ADP-Fossil fuel, HTP, FAETP, and MAETP categories correspond to the 88.48 %, 86.59 %, 49.91%, 37.59 %, and 35.93 %, in their total life cycle impact, respectively.

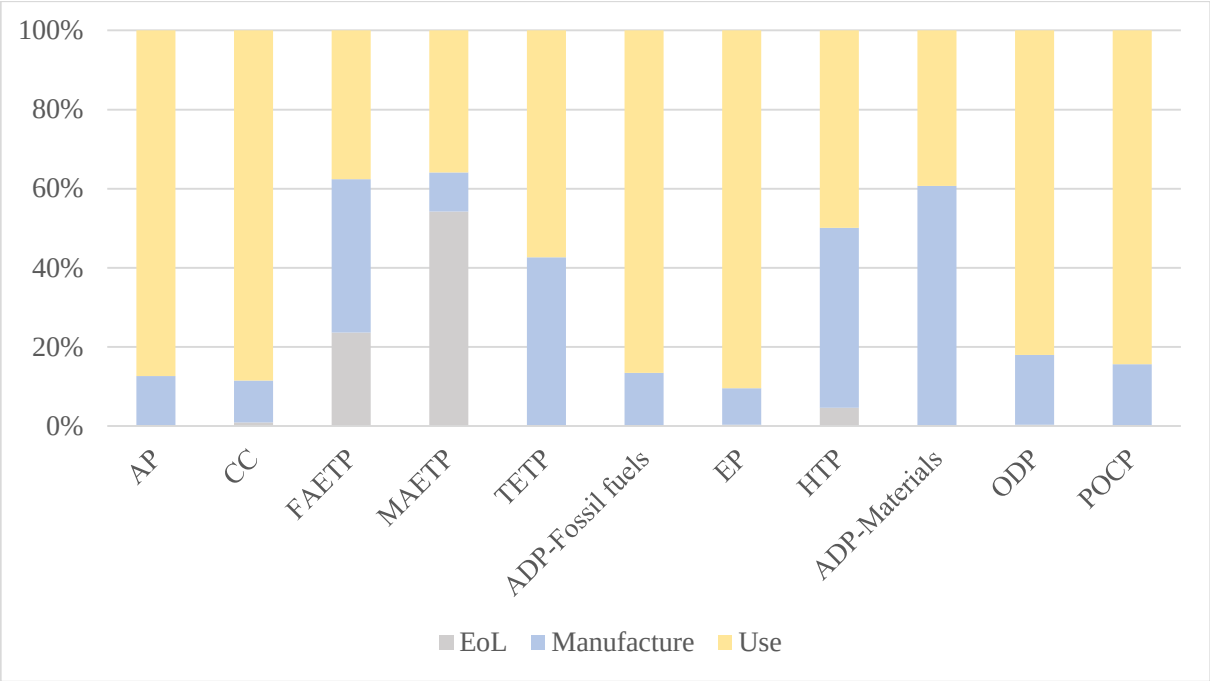

Figure 4.5. Impact ratio in the total lifecycle according to the characterization results of the washing machine in Türkiye 2022 electricity mix scenario (S1).

Considering the causes of these impact categories in whole life cycle impact are analyzed cumulatively as follows for the first scenario of washing machine while mentioning the highest impacted processes:

- CC: 30.05 %, 28.96 % and 10.28 % of the climate change impact have caused by the electricity production from lignite, hard coal, and natural gas from conventional power plant, respectively.
- FAETP: 23.59 %, 19.48 %, and 16.89 % of the freshwater ecotoxicity impact have caused by the treatment of municipal solid waste through incineration, treatment of scrap copper by incineration, treatment of spoil from lignite mining, respectively.
- MAETP: 54.10 %, 13.54 %, and 7.23 % of marine ecotoxicity impact have caused by the treatment of solid waste by incineration, treatment of spoil from lignite mining, and electricity production from hard coal, respectively.
- ADP-Fossil fuel: 25.52 %, 20.50 %, and 12.52 % of abiotic depletion from fossil fuel impact have been caused by the lignite mine operation, hard coal mine operation and preparation, and onshore petroleum and gas production, respectively.
- HTP: The analysis of the highest impacted processes shows that 10.51 %, 14.78 %, and 7.30 % of human toxicity impact have been caused by the treatment of spoil from lignite mining

to be used as electricity all phases, smelting of copper concentrate, and treatment of sulfidic tailings from copper mine operations, respectively while the other 67.41 % impact caused by the other processes cumulatively.

4.2.1. Clean energy mix comparison (S1 and S2)

There was a notable decrease in several environmental impact categories as a result of the 2022–2035 electricity mixes in Türkiye for washing machines as seen in Figure 4.6. More specifically, the impacts of CC decreased by 18.46 %, indicating a significant drop in GHG emissions as a result of switching to a cleaner energy mix mostly in the use phase highly impacted. A reduced rate of depletion of non-renewable energy resources is shown by the 16.74 % decrease in ADP-Fossil fuels. In addition, the reductions in HTP by 4.92%, MAETP by 7.64 %, and FAETP by 4.91 % demonstrate the wider advantages for the environment and public health of switching to a more sustainable electricity mix in this study. Furthermore, these results also comply with the fact that it was discovered that transitioning to a cleaner energy mix could decrease the climate change impacts (Yuan et al., 2016).

Considering the causes of these impact categories in cumulative life cycle impact are analyzed as follows for the clean electricity mix scenarios for 2022 and 2035 in Türkiye comparison of washing machine (S1 and S2):

- CC: While there is 26.69 % impact reduction caused by the electricity production from lignite, 28.99 % decrease in impact due to the electricity production from hard coal, and 14.61 % impact alleviation caused by electricity production from natural gas through conventional power plant.
- FAETP: Lowering the freshwater ecotoxicity impact is caused by the 20.45 % impact reduction in treatment of spoil from lignite mining, 2.34 % decrease in impact due to the treatment of scrap copper through incineration in Türkiye.
- MAETP: 20.18 %, 28.99 %, and 26.96 % marine ecotoxicity impact reductions are seen due to the decrease in treatment of spoil from lignite mining, electricity production from hard coal, and treatment of spoil from hard coal mining, respectively, thanks to cleaner electricity mix in 2035.

- ADP-Fossil fuel: 20.70 %, 28.64 %, and 10.07 % impact reductions are seen in this impact category due to the decrease in lignite mine operation, hard coal mine operation and preparation, and petroleum and gas production, respectively.
- HTP: 20.25 % and 1.25 % impact reductions caused by the treatment of spoil from lignite mining and smelting of copper concentrate for manufacture phase cause less human toxicity potential and the other reasons are mostly sum of the other processes.

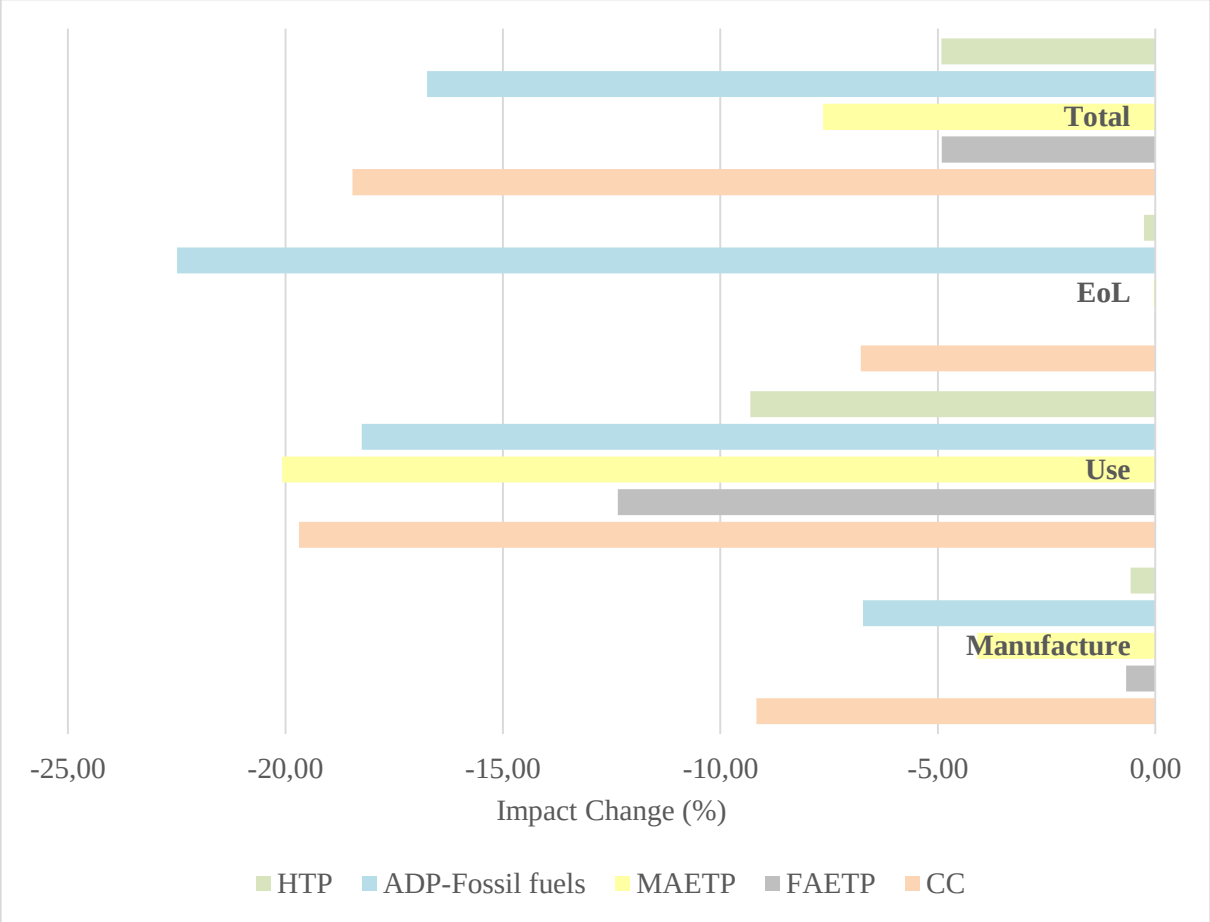

Figure 4.6. Change in characterization results for 2035 electricity mix compared to 2022 electricity mix of the washing machine for each life cycle phases in Türkiye (%).

4.2.2. Durability comparison up to 2053 (S3, S4, and S5)

As seen in Figure 4.7, the weights of the various impact categories in each scenario change with different life cycle phases. For example, the CC effect was 84.70 %, 89.38 %, and 83.07 %; FAETP effect was 32.55 %, 43.84 %, and 29.95 %; MAETP effect was 33.36 %, 48.36 %, and 30.71 %; ADP-Fossil fuels effect was 81.94 %, 87.22 %, and 80.08 %; HTP effect was 42.70 %, 53.19 %, and 39.98 % for the use phase of washing machine in S3, S4, and S5, respectively. In this case, the impacts

of S3 and S5 scenarios in the manufacturing and disposal stages have increased slightly even though more washing machines were manufactured and disposed in scenarios S3 and S5 compared to scenario S4.

When washing machines with longer lifespans (S4) are compared to those with shorter lifespans (S3), the effect of CC is reduced by 5.24 % due to low electricity production from lignite, hard coal, and natural gas in manufacture and end of life phase and low amount of ABS and iron production for manufacturing, ADP-Fossil fuels are reduced by 6.05 % due to low lignite, hard coal mine operation and preparation and natural gas production, FAETP is reduced by 25.75 % due to low treatment of scrap copper and treatment of municipal solid waste through incineration, MAETP is reduced by 31.01 % due to low treatment of municipal solid waste in end of life phase, and HTP is reduced by 19.71 % due to low smelting of copper concentrate and treatment of sulfidic tailings from copper mine operation in total lifecycle impact as seen in Figure 4.7. For several impact categories, these outputs indicate increasing product longevity can lead to substantial environmental savings. When a washing machine's lifespan is extended by 20 years, the impacts of end of life and manufacture in all impact categories can be reduced and there is no change in the use phase because it was anticipated that the washing machine would be replaced with a new model with the same features and energy-saving capabilities.

The environmental effects will vary significantly in certain impact categories if older appliances are replaced with newer, more energy-efficient models. The cumulative life cycle impacts of these impact categories are examined in the following manner for the washing machine comparison between S5 and S3 and S4:

- CC: If renewing the washing machine with the 20 % more energy-efficient one when it reaches its lifetime scenario realized up to 2053 (S5), there is 9.61 % and 4.61 % impact reduction compared to the S3 and S4, respectively. These impact reductions are observed due to the low electricity production and consumption from hard coal, lignite and natural gas in use phase.
- FAETP: While lowering the freshwater ecotoxicity impact in S5 is caused by the 3.72 % impact reduction in treatment of scrap copper when compared to the S3, there is impact increase in S5 compared to S4 as 29.68 % due to the treatment of scrap copper and requiring more manufacture and disposal phase for more appliances used in S5.

- MAETP: While decreasing the marine ecotoxicity impact in S5 is caused by the 3.83 % impact reduction in treatment of municipal solid waste and spoil from lignite mining when comparing to the S3, there is impact increase in S5 compared to S4 as 39.40 % due to the treatment of municipal waste and scrap copper and requiring more manufacture and disposal phase in S5.
- ADP-Fossil fuel: Renewing the washing machine with 20 % more energy-efficient one when it reaches its lifetime scenario up to 2053 results in 9.33 % and 3.49 % impact reduction compared to the S3 and S4, respectively. These impact reductions are observed due to the low electricity production and consumption from hard coal and lignite in use phase of S5.
- HTP: While decreasing human toxicity impact in S5 is caused by the 4.54 % impact reduction in treatment of spoil from lignite mining compared to S3, there is impact increase in S5 compared to S4 as 18.89 % due to the smelting of copper concentrate and treatment of sulfidic tailings from copper mine operations in S5.

The optimal scenario is S5 if reducing the influence of CC and ADP-Fossil fuel is required; the best scenario is S4 if reducing the impact of all of these factors—FAETP, MAETP, ADP-Fossil fuel, and HTP—while preserving the integrity of any impact category is desired for the washing machine.

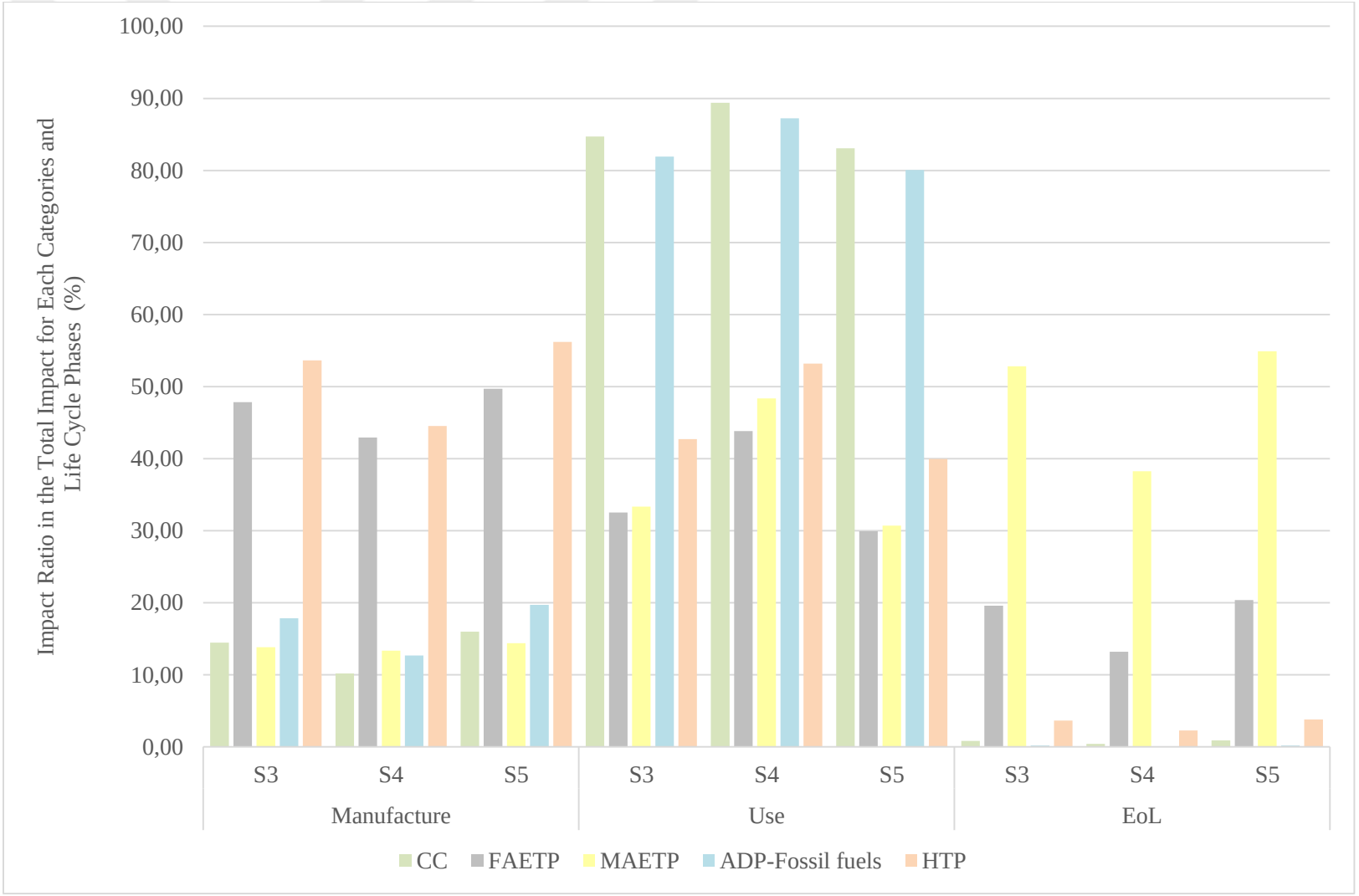

Figure 4.7. Change in characterization results of the washing machine for durability scenario up to 2053 for S3, S4, and S5 (where, S3: Normal lifetime (13) up to 2053, S4: Extended lifetime (20) up to 2053, S5: Normal lifetime (13) up to 2053 and renewing the appliances with 20% more energy-efficient ones).

4.2.3. Consumer choice comparison (S2 and S6)

Significant environmental benefits are achieved when washing machines' energy efficiency is increased by 20 % during use phase). The impacts of CC, ADP-Fossil fuels, FAETP, MAETP, and HTP have decreased by 19.54 %, 19.62 %, 19.67 %, 19.80 %, and 18.31 % in S6, respectively. This implies that using energy-efficient washing machine enhances all environmental impact categories and results in less environmental impact.

The life cycle impact of these categories is investigated and compared in detail as follows for the usage of 20 % more energy-efficient washing machine in Türkiye (S2 and S6):

- CC: There is 20.28 %, 20.26 %, and 20.49 % impact reduction caused by the electricity production from lignite, hard coal, and natural gas through conventional power plant mostly for global warming potential in S6, respectively.
- FAETP: Lowering the freshwater ecotoxicity impact is caused by 20.33 %, 20.41 %, and 20 % reduction in treatment of spoil from lignite mining, treatment of scrap copper, and treatment of spoil from hard coal mining when using 20 % more energy-efficient washing machine in Türkiye.
- MAETP: 20.23 %, 20.24 %, and 20.27 % impact reduction in treatment of spoil from lignite mining, electricity production from hard coal, and treatment of spoil from hard coal mining, respectively, results to decrease the marine ecotoxicity thanks to using more energy-efficient washing machine.
- ADP-Fossil fuel: There is 20.29 %, 19.93 %, and 20.33 % impact reduction caused by the electricity production from lignite and hard coal mine operation and preparation and petroleum and gas production mostly in S6, respectively.
- HTP: 20.14 %, 19.88 %, and 20.13 % impact reduction caused by the treatment of spoil from lignite mining, electricity production from hard coal, and smelting of copper concentrate result in less human toxicity potential when using energy-efficient washing machine, consecutively.

4.2.4. Consumer behavior comparison (S2 and S7)

20 % fewer washing cycles during the use phase (S7 compared to S2) emphasizes how customer behavior affects environmental burdens. In this scenario (S7), the consequences are shown to decrease

by 19.31 %, 13.39 %, 19.44 %, 19.56 %, and 18.09 % in CC, ADP-Fossil, FAETP, MAETP, and HTP compared to S2, respectively and this is closely correlated with fewer frequent usage of washing machine. These results also comply with improving washing machine efficiency resulting in a decrease climate change impacts (Yuan et al., 2016). Furthermore, running a washing machine 3 times in a week as opposed to 4 times is almost equal to using 20 % more efficient washing machine. This conclusion might also be achieved by the implementation of the circular business including pay-per-wash as discussed in the study conducted by Sigüenza et al. (2021).

For the 20 % less washing cycle in the use phase of washing machine, the causes of these impact categories in the life cycle impact are investigated and compared with the baseline scenario (S2 and S7). The results show that the impact reduction reasons are almost the same with the comparison of 20 % more energy-efficient washing machine usage (S2 and S6) for CC, FAETP, MAETP, ADP-Fossil fuel, and HTP. There is a slight change as less than 1.5 % and this is caused by the water consumption dependent on the washing cycle and does not change with electricity consumption.

As in this study discussing consumer behavior, Sigüenza et al. (2021) also examine the environmental and material implications of adopting circular business models such as pay-per-wash for washing machines. It is found that users lowered the average temperature of the washing cycles by 5 % and the monthly number of cycles by 20 % and environmental impact has decreased in CC. Rather than the electricity consumption, the emphasis on material use and the environmental implications of production methods likely contribute to the MAETP and FAETP impacts. Sigüenza et al. do not specifically address ADP-Fossil fuel, their focus on the material use and production phase implies a significant energy and resource footprint associated with the manufacturing of washing machines.

4.2.5. Consumer choice and behavior comparison (S2 and S8)

The biggest environmental gains are achieved when 20% fewer washing cycles and improved energy efficiency are combined in S8. The environmental impacts of S8 imply striking reduction as 34.95 %, 35.18 %, 35.40 %, 35.08 %, and 32.73 % in CC, FAETP, MAETP, ADP-Fossil fuels, and HTP, consecutively. This case illustrates the mutually reinforcing advantages of combining consumer behavior changes with technology advancements in order to achieve environmental sustainability.

The following analysis and comparison are made for the combination of more energy-efficient washing machine and less washing cycle usage (S2 and S8) considering the sources of these impact categories in the life cycle:

- CC: There is 36.15 %, 36.15 %, and 36.40 % impact reduction caused by the electricity production from lignite, hard coal, and natural gas through conventional power plant mostly in S8, respectively.
- FAETP: Lowering the freshwater ecotoxicity impact is caused by 36.24 %, 36.33 %, and 36.10 % reduction in treatment of spoil from lignite mining, treatment of scrap copper, and treatment of spoil from hard coal mining in the combination of more energy-efficient and less washing cycle scenario.
- MAETP: 36.42 %, 36.14 %, and 36.26 % impact reduction in treatment of spoil from lignite mining, electricity production from hard coal, and treatment of spoil from hard coal mining, respectively, led to alleviate the marine ecotoxicity in S8.
- ADP-Fossil fuel: There is 36.18 %, 36.23 %, and 36.18 % impact reduction caused by the electricity production from lignite and hard coal mine operation and preparation and petroleum and gas production mostly in S8, consecutively.
- HTP: 36.16 %, 36.14 %, and 36.17 % impact reduction caused by the treatment of spoil from lignite mining, electricity production from hard coal, and smelting of copper concentrate result in less human toxicity potential in S8, respectively.

As seen in Figure 4.8, the highest environmental savings can be achieved with the combination of 20 % more energy-efficient with 20 % less washing cycle for washing machine. Although there is a slight change between S6 and S7 in all impact categories, the second-best scenario is the 20 % more energy-efficient washing machine usage and it can be concluded that using a washing machine 3 times a week as opposed to 4 is almost equivalent to using 20 % more efficient dishwasher while reducing the washing cycle by 20 % in a year.

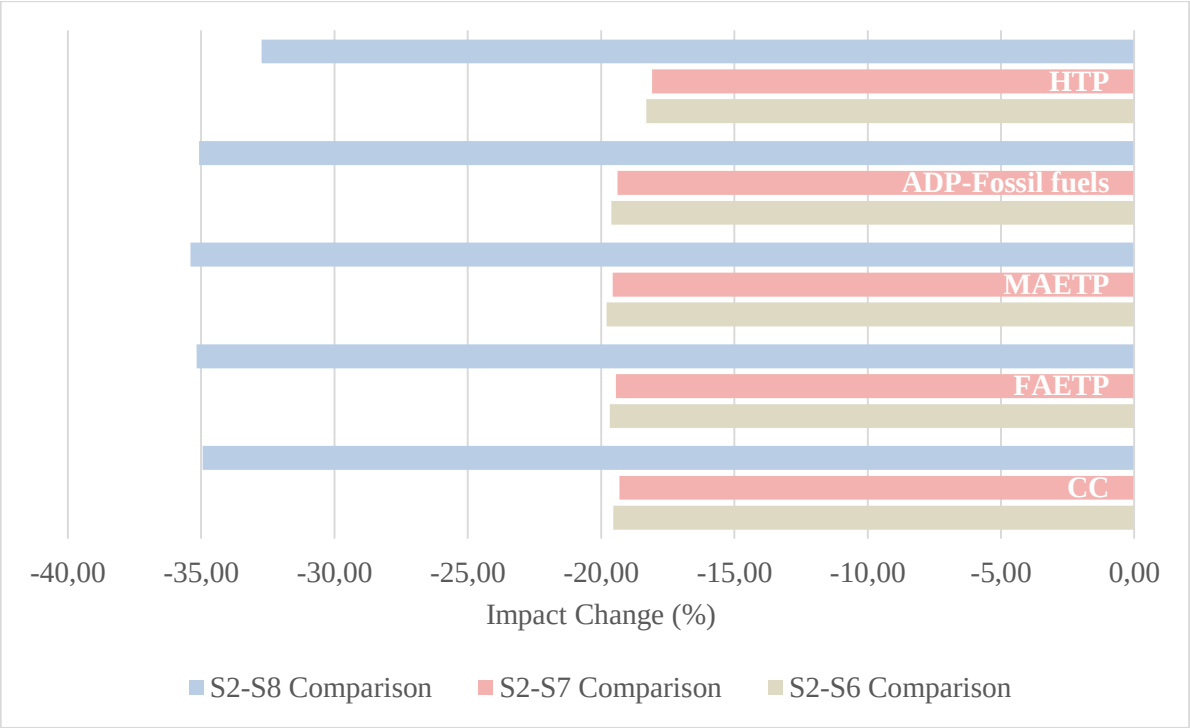

Figure 4.8. Impact change comparison between S2 and S6, S7, and S8 for each impact categories for washing machine (%) (where, S2: 2035 Electricity mix in Türkiye, S6: 20 % more energy-efficient dishwasher, S7: 20 % of washing cycle reduction, and S8: 20 % more energy-efficient appliance selection and 20 % of washing cycle reduction).

4.3. LCA Results of Refrigerator

As seen in Figure 4.9 and mentioned in the study, the use phase of the refrigerator is crucial in establishing its sustainability because of its extended lifespan, and high energy consumption (Gasia et al. 2021). The use phase of the refrigerator has the highest load when compared to other life cycle phases excluding ADP-Materials (60.09 %) caused mostly by electrorefining of copper and FAETP (42.78 %) due to the treatment of the scrap copper in manufacture phases. Due to electricity consumption from fossil fuels, the usage phase has the biggest burden for the other impact categories. Use phase impact for MAETP, ADP-Fossil fuel, FAETP, HTP, and CC categories correspond to the 48.23 %, 86.07 %, 42.65 %, 51.91 %, and 85.06 % in their total life cycle impact, respectively (Figure 4.9).

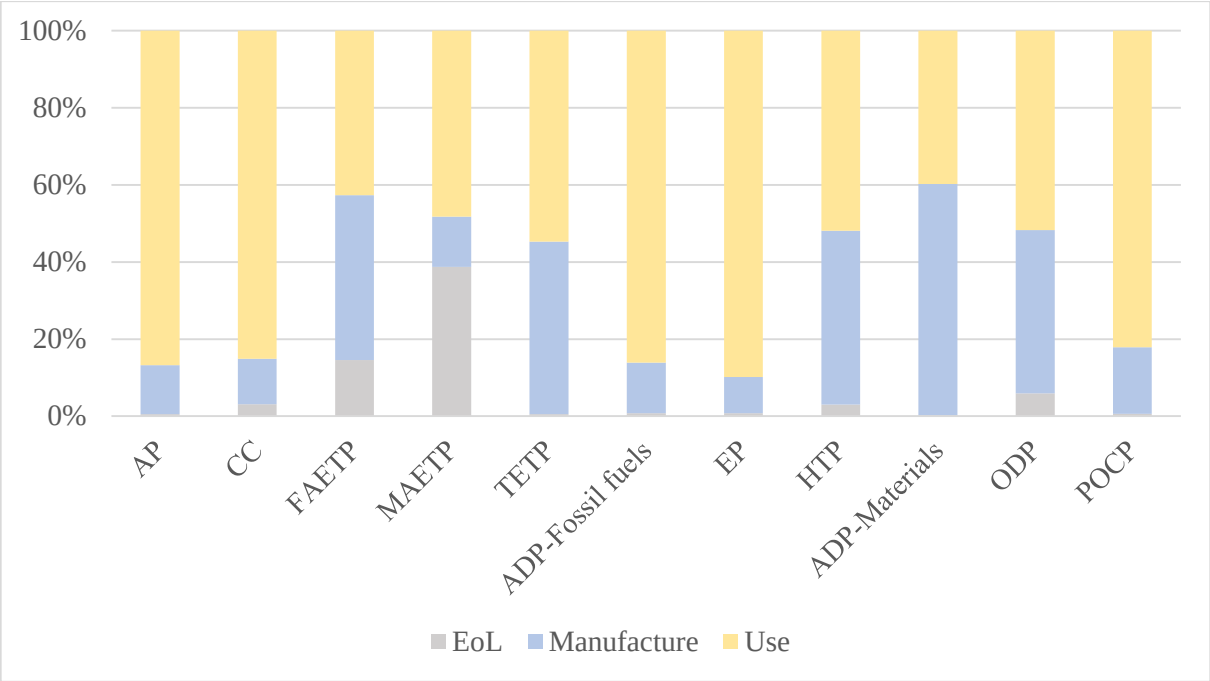

Figure 4.9. Impact ratio in the total lifecycle according to the characterization results of the refrigerator in Türkiye 2022 electricity mix scenario (S1).

Considering the causes of these impact categories in whole life cycle for cumulative impact are analyzed as follows for the first scenario of refrigerator while mentioning the highest impacted processes:

- CC: 29.10 %, 28.01 % and 9.69 % of the climate change impact have caused by the electricity production from lignite, hard coal, and natural gas from conventional power plant, respectively.
- FAETP: 21.81 %, 19.37 %, and 14.26 % of the freshwater ecotoxicity impact have caused by treatment of scrap copper by municipal incineration, the treatment of spoil from lignite mining, and treatment of municipal solid waste through incineration, respectively.
- MAETP: 38.40 %, 18.24 %, and 9.66 % of marine ecotoxicity impact have caused by the treatment of solid waste by incineration, treatment of spoil from lignite mining, and electricity production from hard coal, respectively.
- ADP-Fossil fuel: 25.54 %, 20.66 %, and 12.48 % of abiotic depletion from fossil fuel impact have caused by the electricity production processes covering lignite and hard coal operation and preparation, and natural gas production, respectively.

- HTP: 15.53 %, 11.78 %, and 7.84 % of human toxicity impact have caused by the smelting of copper concentrate, treatment of spoil from lignite mining to be used as electricity all phases, and treatment of sulfidic tailings from copper mine operations, respectively.

4.3.1. Clean energy mix comparison (S1 and S2)

Considerable environmental effect savings occur when refrigerators switch from 2022 to 2035 electricity mix (S1 to S2). A cleaner energy mix appears to have contributed to a significant decrease in GHG emissions, as seen by the 17.42 % decrease in CC effects. The reductions in HTP by 5.35 %, MAETP by 9.96 %, and FAETP by 5.44 % further emphasize the wider ecological and public health advantages of this future electricity mix. The 16.30 % decrease in the ADP-Fossil fuels suggests a slower rate of non-renewable energy resource depletion in cleaner electricity mix. This results also complies with the fact that energy grid with a high share of renewable sources has a low environmental impact throughout usage phase (Rossi et al., 2021). Furthermore, Lewandowska et al. (2021) state that more environmental savings are achieved when durable products are sent to be used in countries with better national energy mixes than worst national energy mixes. Impact change for each life cycle phase and impact categories can be seen in Figure 4.10.

The sources of these impact categories in the cumulative life cycle impact are examined for the clean electricity mix scenarios in Türkiye's refrigerator comparison for the years 2022 and 2035 (S1 and S2) as follows:

- CC: While there is 19.97 % impact reduction caused by the electricity production from lignite, 28.27 % decrease in impact due to the electricity production from hard coal, and 13.91 % impact alleviation caused by electricity production from natural gas through conventional power plant.
- FAETP: Lowering the freshwater ecotoxicity impact is caused by the 19.60 % impact reduction in treatment of spoil from lignite mining, 2.35 % decrease in impact due to the treatment of scrap copper through incineration.
- MAETP: 19.74 %, 28.20 %, and 25.27 % marine ecotoxicity impact reductions are seen due to the decrease in treatment of spoil from lignite mining, electricity production from hard coal, and treatment of spoil from hard coal mining, respectively in cleaner electricity mix scenario.

- ADP-Fossil fuel: 19.85 %, 28.04 %, and 27.03 % impact reductions are seen in this impact category due to the decrease in lignite mine operation, hard coal mine operation and preparation, and petroleum and gas production, respectively.

  HTP: 19.58 % and 1.18 % impact reductions caused by the treatment of spoil from lignite mining and smelting of copper concentrate in manufacture phase cause less human toxicity potential and the other reasons are mostly the sum of the other processes.

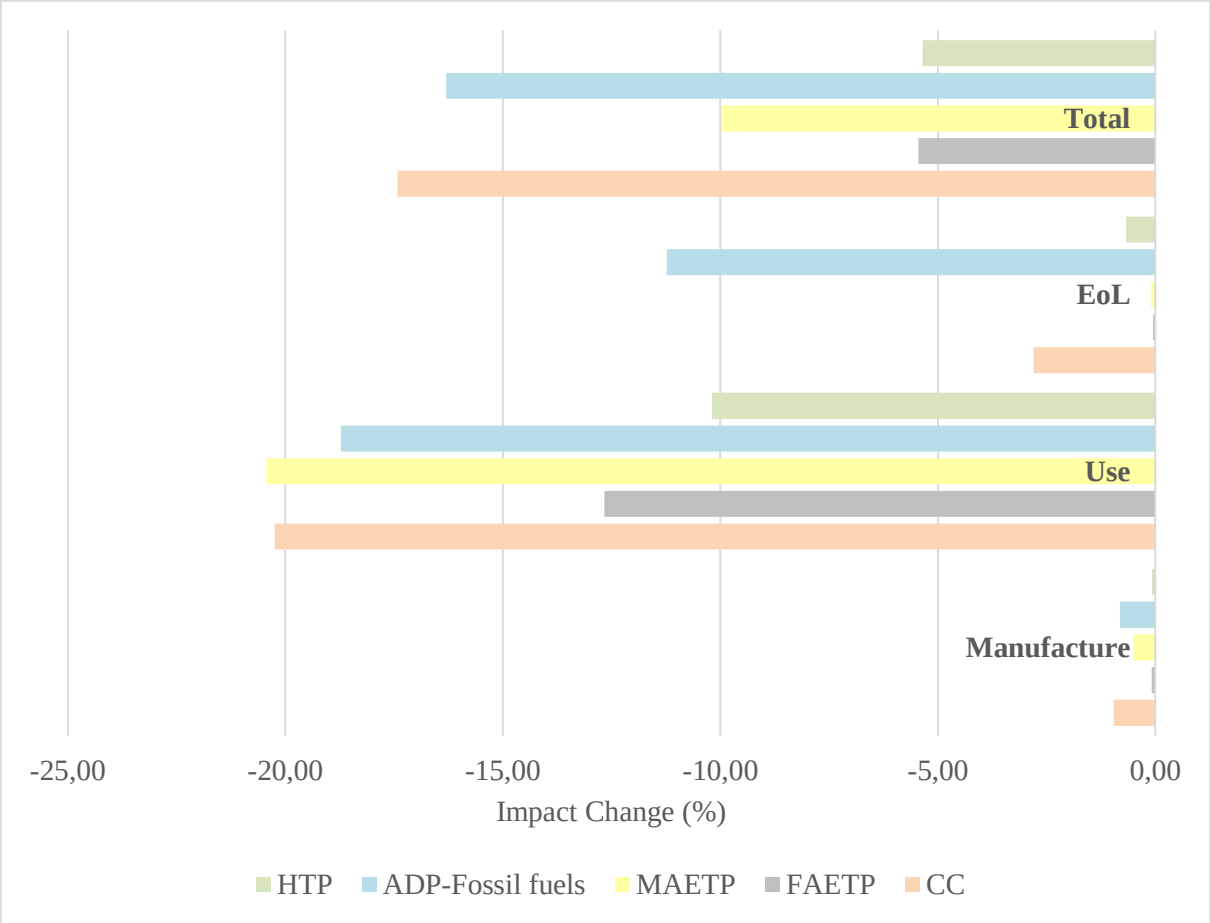

Figure 4.10. Change in characterization results for 2035 electricity mix compared to 2022 electricity mix of the refrigerator for each life cycle phases in Türkiye (%).

4.3.2. Durability comparison up to 2053 (S3, S4, and S5)

As shown in Figure 4.11, the weights of different impact categories in each scenario change with different life cycle phases. To illustrate, the CC effect was 79.69 %, 85.93 %, and 77.62 %; FAETP effect was 36.08 %, 47.02 %, and 33.28 %; MAETP effect was 44.03 %, 58.60 %, and 41.01 %; ADP-Fossil fuels effect was 80.46 %, 86.17 %, and 78.44 %; HTP effect was 44.06 %, 54.42 %, and 41.04 % for the use phase of refrigerator in S3, S4, and S5, respectively. In this case, even though the

impacts of S3 and S5 scenarios in the manufacturing and disposal stages have increased slightly due to more appliances manufactured and disposed in scenarios S3 and S5 compared to scenario S4.

If refrigerator with longer lifespans (S4) are compared to those with shorter lifespans (S3), the effects of CC is reduced through manufacture and end of life phase by 7.26 % due to low electricity production from lignite, hard coal, and natural gas, ADP-Fossil fuels are reduced by 6.62 % due to low lignite, hard coal mine and natural gas operation and preparation, FAETP is reduced by 23.28 % due to low treatment of scrap copper and municipal solid waste through incineration, MAETP is reduced by 24.86 % due to less municipal solid waste treatment through incineration and treatment of spoil from lignite in disposal phase, and HTP is reduced by 19.04 % due to less treatment in spoil from lignite and smelting of copper concentrate in total lifecycle impact as seen in Figure 4.11. For some of the impact categories, increasing product durability can lead to worthy environmental savings due to the decreased need for manufacture and disposal in the extended lifetime scenario (S4). When the lifetime extension of the refrigerator as of 20 years, the end of life and manufacture impacts in all impact categories can be decreased by 50 % and 33.33 %, consecutively and no change in the use phase ever occurs because of the assumption about renewing with the same featured refrigerator.

When more energy-efficient appliances are used while replacing with the newest and energy-efficient refrigerator, the environmental impacts will change substantially in some of the impact categories. The following analysis is done for the refrigerator comparison of S5 with S3 and S4, taking into account the sources of these categories in the cumulative life cycle impact:

- CC: If renewing the refrigerator when it reaches its lifetime scenario realized up to 2053 (S5), there is 9.25 % and 2.15 % impact reduction compared to the S3 and S4, respectively. The low electricity consumption especially through hard coal and lignite in the use phase is the reason for the impact reduction in global warming potential.
- FAETP: While lowering the freshwater ecotoxicity impact in S5 is caused by the 4.19 % impact reduction in treatment of spoil from lignite mining when compared to the S3, there is impact increase in S5 compared to S4 as 24.88 % due to requiring high the treatment of scrap copper and spoil from lignite mining in manufacture and disposal phase for more refrigerator used in S5.
- MAETP: While decreasing the marine ecotoxicity impact in S5 is caused by the 5.11 % impact reduction in treatment of spoil from lignite mining if compared to the S3, there is impact

increase in S5 compared to S4 as 26.29 % due to the treatment of municipal waste through incineration and scrap copper during more manufacture and disposal phase in S5.

- ADP-Fossil fuel: Renewing the dishwasher when it reaches its lifetime scenario realized up to 2053 results in 9.34 % and 2.91 % impact reduction compared to the S3 and S4, respectively. These impact reductions are analyzed due to the low electricity production and consumption from hard coal and lignite in use phase of S5.
- HTP: While treatment of spoil from lignite mining and electricity production from hard coal have a 5.12 % impact reduction in S5 compared to S3, the smelting of copper concentrate and treatment of sulfidic tailings from copper mine operations in S5 result in 17.20 % impact increase in S5 compared to S4.

In summary, the optimal scenario is S5 if reducing the impact of CC and ADP-Fossil fuel is intended; the best scenario is S4 if reducing all impact categories covering CC, FAETP, MAETP, ADP-Fossil fuel, and HTP without harming any environmental body is desired.

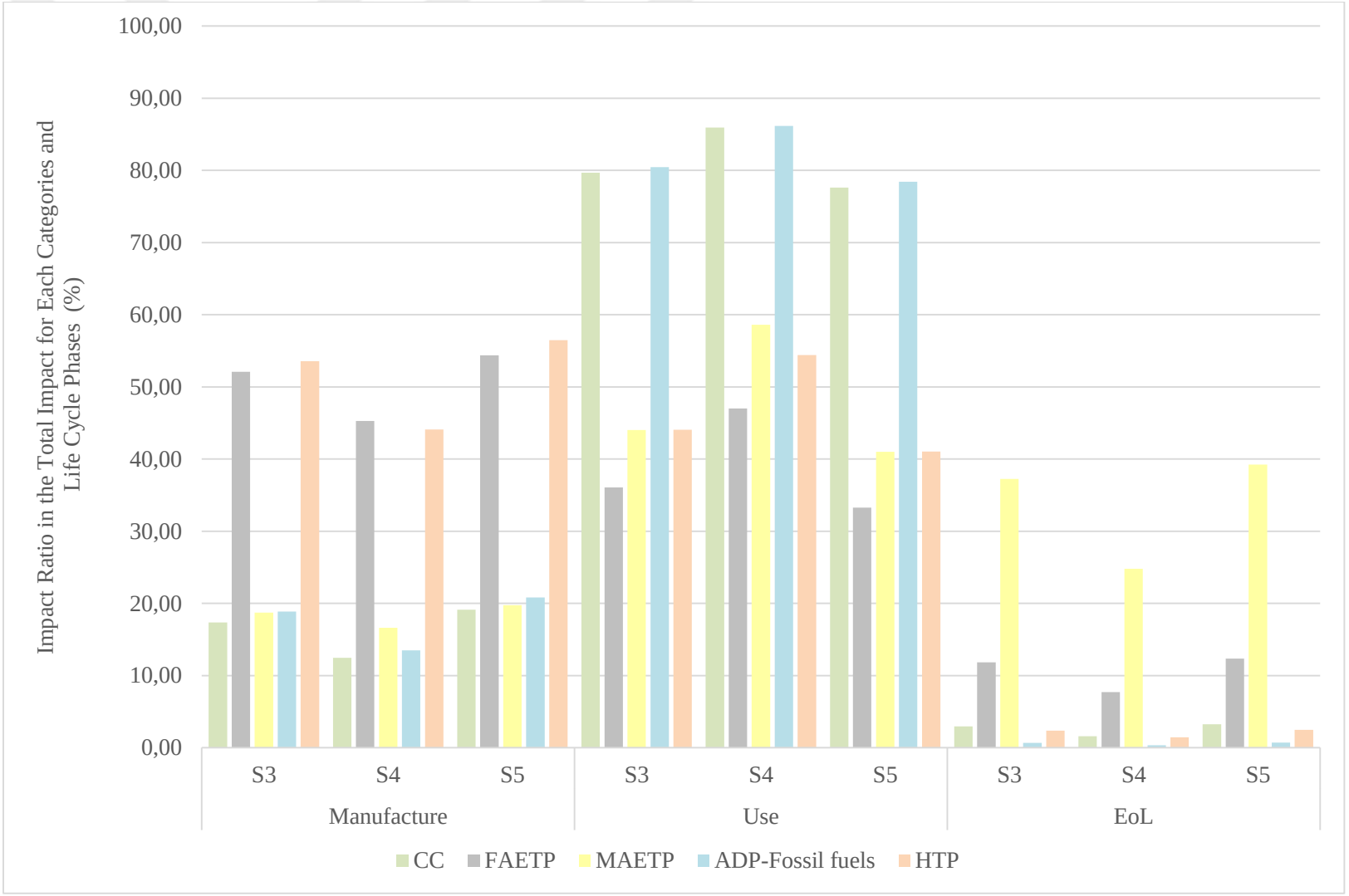

Figure 4.11. Change in characterization results of the refrigerator for durability scenario up to 2053 for S3, S4, and S5 (where, S3: Normal lifetime (13) up to 2053, S4: Extended lifetime (20) up to 2053, S5: Normal lifetime (13) up to 2053 and renewing the appliances with 20% more energy-efficient ones).

4.3.3. Consumer choice comparison (S2 and S6)

A uniform 20 % decrease in all environmental impact categories including CC, ADP-Fossil fuels, FAETP, MAETP, and HTP is achieved by applying a 20 % increase in energy efficiency during the refrigerator's use phase (S6 compared to S2). This consistent decrease in all of these different categories highlights how successful energy efficiency is in reducing threats to the environment, human health, and non-renewable resources while also reducing climate change. As Rossi et al. (2021) mentioned higher energy-efficient refrigerator with low electricity consumption reduces the emissions caused by the use phase.

The life cycle impact of these categories is evaluated and compared in the detailed as follows for the usage of 20.00 % more energy-efficient refrigerators in Türkiye (S2 and S6):

- CC: Almost 20.00 % impact reduction in global warming potential caused by the electricity production from lignite, hard coal, and natural gas through conventional power plant in S6 compared to S2.
- FAETP: Lowering the freshwater ecotoxicity impact is caused by 20.00 %, 20.12 %, and 20.42% reduction in treatment of spoil from lignite mining, treatment of scrap copper, and treatment of spoil from hard coal mining in S6.
- MAETP: 20.17 %, 20.03 %, and 20.20 % impact reduction in treatment of spoil from lignite mining, electricity production from hard coal, and treatment of spoil from hard coal mining, respectively.
- ADP-Fossil fuel: There is 20.08 %, 19.90 %, and 20.00 % impact reduction caused by the electricity production from lignite and hard coal mine operation and preparation and petroleum and gas production for natural gas, respectively.
- HTP: 19.87 %, 20.00 %, and 20.00 % impact reduction caused by the treatment of spoil from lignite mining, electricity production from hard coal, and smelting of copper concentrate result less human toxicity potential, consecutively.

The scenarios for consumer behavior (S7) and both consumer choice and behavior (S8) comparison are not applicable for refrigerator. Even though S8 includes the energy efficiency, it will be the same with S6 in consumer behavior comparison (S2 and S8) due to no washing cycle in refrigerator.

Regarding both scenarios developed for the refrigerator, the study on household refrigerators in China provides valuable insights into the elevated values for MAETP and FAETP in this research, especially in all scenarios use phase has the highest impacts and this result differs from this study. For the CC impact, the usage phase of refrigerators is a dominant contributor, mainly due to electricity consumption. This observation aligns with the high CC values in this research particularly those representing the use phase of appliances. Furthermore, opportunity for improvement targets one or more hotspots by lowering the environmental harms or increasing environmental benefits. These prospects cover the product design advancements developments in manufacturing phase, customer encouragement, supply chain optimization, and so on. Since the usage phase is the most responsible for the majority of the environmental impacts, daily consumer behaviors should be encouraged as reducing electricity consumption through less energy consuming product selection regarding the energy efficiency labels, placing refrigerators for good ventilation and out of the direct sunlight, not putting hot food in the refrigerator to stabilize the internal temperature, storing less food to be stored in refrigerator to decrease storage time, and minimizing the number of times the door is opened and closed which may save up to 7 % electricity usage. Also, due to the excessive usage of the components increasing the electricity consumption, old refrigerators should be retired if it reaches an acceptable age (Xiao et al., 2015).

4.4. Evaluation for LCA Results of All Selected Household Appliances

As stated in the previous part of this study, achieving environmental sustainability and lowering hazards to human health can be supported by enhancing cleaner energy mix, behavioral and choice change in consumers, and improving durability. Evaluation of all scenarios is given in Figure 4.12 for all of the appliances in a year to compare all scenarios in similar bases. Some parameters (refrigerant leakage for refrigerators, and detergent use for dishwashers and washing machines) could not be included in this study. Because each appliance was compared within each scope in this study and it will be neglected because of being the constant data in the comparison and lack of reliable data. This assumption prevents a reliable comparison of environmental impacts of appliances between each other and that’s why this study does not give information about the environmental impact comparison of refrigerator, dishwasher, and washing machine between themselves. Evaluation of the environmental impact for 1 year as given in Figure 4.12 shows that switching to the 2035 electricity mix (S2) lowers all environmental effects and S1 has higher impact than S2 as 20 % more for both appliances. While dishwasher represents the highest decrease, refrigerator gives the lowest reduction in cleaner electricity mix. The analysis of the durability scenarios shows that refrigerator, washing machine, and dishwasher have the environmental gains about climate change impact mitigation from

highest to lowest for S4, 4.4 %, 2.5 %, and 1.3 % compared to S2, respectively. Analysis of the consumer choice scenario (S6) gives insight about the fact that dishwasher is affected more and refrigerator is affected less when compared to washing machine. Selecting 20 % more energy-efficient appliances (S6) and reducing the number of washing cycles (S7) results in additional benefits and the most notable decrease in environmental consequences is seen by the combination of these measures as in S8 for washing machine and dishwasher. Within the context of this study, transition to the cleaner energy mix shows the highest impact change compared to S2, and the 20 % more energy-efficient and less washing cycle combined scenario (S8) for all appliances represents the second highest impact change (it applies for the energy-efficient one in refrigerator) considering the global warming potential. After that, while decreasing the washing cycle as 20 % shows the higher environmental benefits for the dishwasher compared to the energy efficiency scenario, using the 20 % more energy-efficient washing machine generates less environmental impact compared to the less washing cycle scenario. For transition to 2035 electricity mix, the environmental effects of switching to the 2035 electricity mix were greatly minimized with more renewable options and energy-saving options would have also better environmental performance due to the direct impact on the use phase as discussed in the study implemented by Binstock et al. (2013). Furthermore, as given in the study conducted by Yuan et al. (2016), detergent use and wastewater discharge have the highest impact on some of the related impact categories, and electricity consumption is the main reason for these impacts as found in this study. Electricity generation mix mentioned in the National Energy Plan of the Türkiye promotes the clean energy mix which is one of the key solutions to make large household appliances more sustainable. Within that context, key stakeholders in this scenario are government and manufacturers. Government and policymakers have major influence in ensuring the widespread use of renewable energy to reduce environmental impacts. Manufacturers should assess the energy mix of the countries where their products are exported and develop solutions to reduce their Scope 3 (Category 5 according to the ISO 14064-1: 2018) emissions. In this context, they can develop financial incentives to use their products in countries with a more environmentally friendly energy mix.

Optimization cost presents a barrier to consumer decision-making and previous studies give information about the impact of energy and financial literacy on energy-efficient household appliances choices. Decision aids including informative materials and online calculator for their cost-effectiveness have potential to empower consumers to pick energy-efficient appliances. Online calculator for the lifetime cost calculation via energy efficiency shows stronger effectiveness in consumer choices while compared with the informative materials. This shows that rational decision-making should always be corrected through tools (Blasch, Filippini, Kumar, and Martinez-Cruz,

2022). It is critical to raise consumer expectations about how long they can use appliances to prolong their lifespan and this perspective might assist to postpone replacing or discarding appliances. Policies should prioritize making improvements to services and appliances designs to increase upgradability, repairability, and durability. It is inefficient to only provide consumers with appliances and services for increasing its longevity, consumers also need to understand and profit from the longer product lifespans. Therefore, legislation should support appliances' functional and physical longevity and offer incentives to consumers about using them longer (Nishijima and Oguchi, 2022). There are drivers including environmental knowledge, consumer attitude, green trust, and purchase intention for consumers' intentions to buy eco-friendly household appliances. While consumer survey results shows that environmental knowledge positively affects consumer attitude and green trust, consumer attitude has negative impact on purchase intention due to investment price and distrust the green claims. Thus, maintaining a rational perspective helps consumers to participate the behavioral change for eco-friendly choices (Asif, Zhongfu, Irfan, and Işık, 2022). These concerns should be considered and good practices should be applied through responsible stakeholders.

Within the scope of consumer behavior and choice change scenarios, government, policymakers, manufacturers, and consumers are responsible for decreasing the environmental burdens in the use phase. Government and policymakers should inform the public about the use of energy-efficient products in white goods and support manufacturers to develop energy-efficient products. In this context, the Ministry of Energy and Natural Resources published Türkiye's Energy Efficiency Strategy and the 2nd National Energy Efficiency Action Plan for 2024-2030 in January 2024. In action given in this Plan for buildings, it is stated that "additional financial incentives will be defined for the replacement of best-in-class energy consuming equipment, home automation systems, and digital technologies" will be realized until 2027 (Ministry of Energy and Natural Resources, 2024). This means that government will support the energy-efficient household appliances in Türkiye. Manufacturers are responsible for improving energy-efficient household appliances and developing their durability with developing maintenance and repair of the appliance even starting in the design phase. Also, manufacturers might be a part of informing the consumers about their impact and responsibilities during use phase of the appliances. Consumers are responsible for their actions while purchasing a new product by regarding the energy labelling if their older appliances are not efficient anymore and decreasing washing cycle by 20 % which means the using dishwasher 4 times in a week instead of 5 and using washing machine 3 times instead of 4 in a week changes results as almost similar to the using 20% more efficient household appliances.

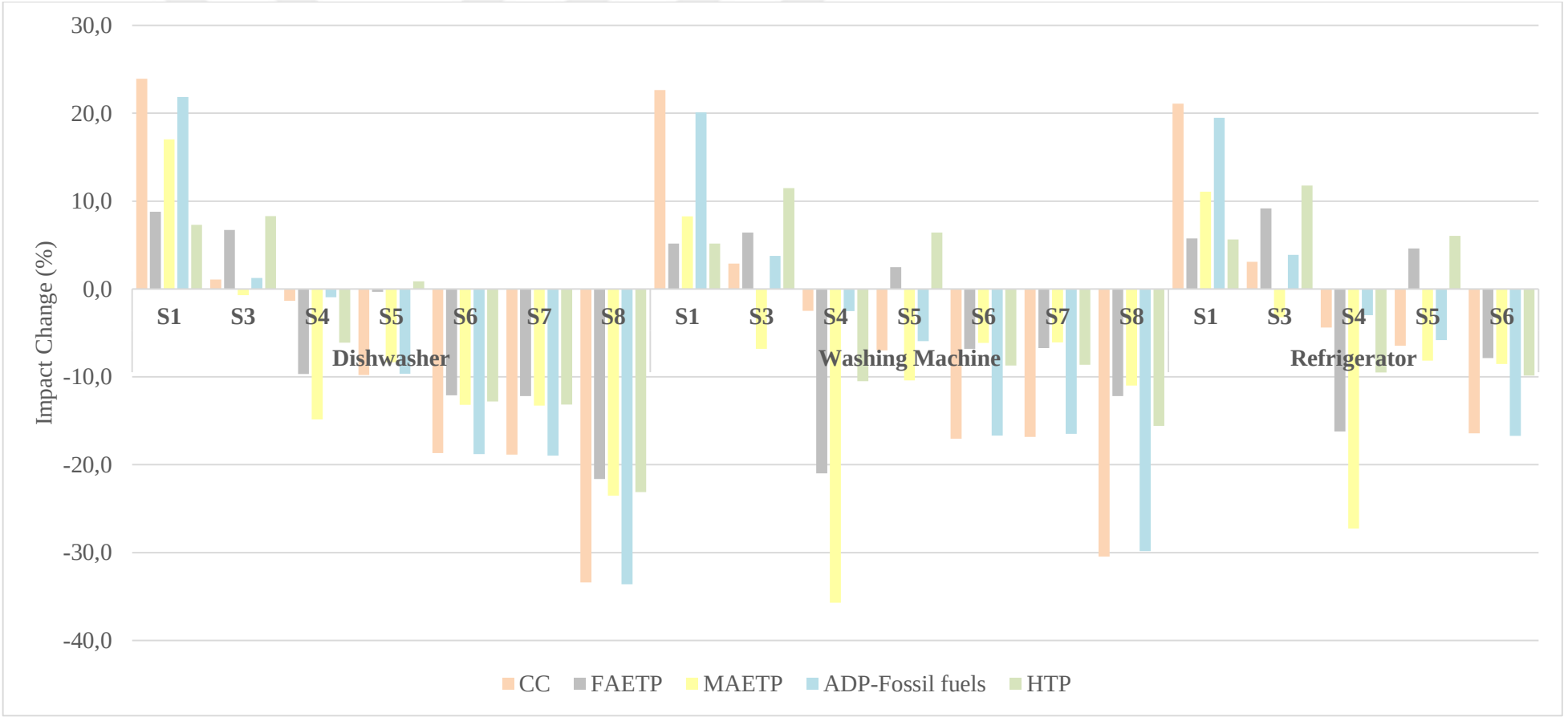

Figure 4.12. Summary of impact change comparison between S2 and the other scenarios for 1 year impact through all lifecycle phases (where, S1: 2022 Electricity mix in Türkiye, S2: 2035 Electricity mix in Türkiye, S3: Normal lifetime (13) up to 2053, S4: Extended lifetime (20) up to 2053, S5: Normal lifetime (13) up to 2053 and changing the newest appliances with 20% more energy-efficient ones, S6: 20% more energy-efficient appliance, S7: 20% of washing cycle reduction for dishwasher and washing machine, and S8: 20% more energy-efficient appliance selection and 20% of washing cycle reduction for dishwasher and washing machine).

As environmental impacts are widely observed today, and considering the emission commitments of countries including Türkiye, many legislation and strategy documents are being published in the EU and Türkiye to reduce environmental impacts. These legislations support the purchasing the energy-efficient household appliances, recycling of more materials, transitioning to the cleaner energy mix, enhancing consumer behavior, innovating environmentally friendly materials and techniques as mentioned in Section 2. Since Türkiye follows the EU documents and integrate them into its policy, it will give insight about the future policies in Türkiye. In Table 4.1 relevant EU documents and SDG targets for this study have been given for the relevant scenarios and circular economy pillar.

Focusing on the switch to sustainable energy sources, the EU Green Deal, Fit for 55, and REPowerEU programs support the shift to the 2035 electricity mix (S2). S2 demonstrates a considerable decrease in the environmental effects of all appliances. The policy background points to a significant convergence with the EU's more general objectives for reducing carbon emissions and promoting energy sustainability.

Durability scenarios analyzed for 2053 when Türkiye aims to reach its net zero target support policies as EU Green Deal, Fit for 55, Critical Raw Material Act, Circular Economy Action Plan, and the Right to Repair initiatives. An important circular economy strategy is extending the lifespan of appliances (S4) and renewing the appliances with the more energy-efficient ones (S5) which also aligns with EU resource efficiency and waste reduction efforts. This reduces the need for the resource-intensive manufacturing of new appliances by rethink during the design phase of the appliances to be repairable easily in the service life.

Consumer behavior and choice scenarios covering the reduction of the washing cycles (S8) and the energy efficiency (S6) both greatly lessen the influence on environment. Promoting these adjustments is in line with EU Energy Efficiency Directive, New Consumer Agenda, Circular Economy Action Plan, and the Proposal for Eco-design for Sustainable Products Regulation which support environmentally friendly customer choices and product design.

Descriptions of the targets aligned with the SDGs supported by this study are provided below (United Nations, 2015):

- Target 6.4: Improving the water consumption efficiency in all sectors by 2030.
- Target 7.1: Ensuring the modern, affordable, and reliable energy services by 2030.

- Target 7.2: Raising the share of renewable energy in the world's energy mix by 2030.
- Target 7.3: Doubling the rate of increase in energy efficiency worldwide by 2030.
- Target 9.4: Upgrading the infrastructure and retrofit industries to become more resource efficient and adopt clean technologies by 2030.
- Target 12.1: Implementing the sustainable consumption and production patterns programmes.
- Target 12.2: Achieving the sustainable management and efficient use of natural resources by 2030.
- Target 12.5: Reducing waste generation through prevention, reduction, recycling, and reuse by 2030.
- Target 12.7: Encouraging sustainable public procurement in line with national priorities and policies.
- Target 12.8: Assuring that public is informed about sustainable development and lifestyles by 2030.
- Target 13.1: Strengthening the resilience to climate related hazards and natural disasters in all countries.
- Target 13.3: Developing knowledge, awareness, and capacity on climate change adaptation and mitigation.

Table 4.1. EU documents related to the scenarios developed considering circular economy pillars analyzed in this study.

Relevant Circular Economy Pillars	Scenarios	Supported SDG Targets		Supported EU Documents
Electricity Mix	S1: Türkiye 2022 Electricity Mix	-		EU Green Deal Fit for 55 REPowerEU
	S2: Türkiye 2035 Electricity Mix	Target 7.1 Target 7.2 Target 12.2	Target 13.1 Target 13.3	
Durability	S3: Normal Lifetime (13) up to 2053	-		EU Green Deal Fit for 55 Critical Raw Material Act Circular Economy Action Plan Right to Repair
	S4: Extended Lifetime (20) up to 2053	Target 9.4 Target 12.1 Target 12.2 Target 12.5	Target 12.7 Target 12.8 Target 13.1 Target 13.3	
	S5: Normal Lifetime (13) up to 2053 and Changing the Newest Appliances With 20% More Energy-Efficient Ones	Target 7.3 Target 12.1 Target 12.2 Target 12.7	Target 12.8 Target 13.1 Target 13.3	
Consumer Choice/Behavior	S6: 20% More Energy Efficiency with 2035 Electricity Mix in Use Phase	Target 7.3 Target 12.1 Target 12.2 Target 12.7	Target 12.8 Target 13.1 Target 13.3	EU Energy Efficiency Directive EU New Consumer Agenda Proposal for Eco-design for Sustainable Products Regulation
	S7: 20% Washing Cycle Reduction with 2035 Electricity Mix in Use Phase	Target 6.4 Target 12.1 Target 12.2 Target 12.5	Target 12.7 Target 12.8 Target 13.1 Target 13.3	EU Green Deal Fit for 55 Circular Economy Action Plan EU New Consumer Agenda
	S8: 20% Washing Cycle Reduction and 20% More Energy Efficiency with 2035 Electricity Mix in Use Phase (Combination of S6 and S7)	Target 7.3 Target 12.1 Target 12.2 Target 12.7 Target 12.8 Target 13.1	Target 13.3	EU Green Deal Fit for 55 Circular Economy Action Plan EU New Consumer Agenda Proposal for Eco-design for Sustainable Products Regulation

5. CONCLUSION

This study has been completed to measure environmental footprint of the selected household appliances and provide possible solutions for decreasing the emerging environmental burdens caused by the use phase of these appliances including refrigerator, washing machine, and dishwasher in Türkiye in various future scenarios related to circular economy approaches to promote Türkiye's net zero target by 2053 via LCA. Within the scope of the study, each of the assessed scenarios offers a unique path toward environmental sustainability, emphasizing the importance of consumer behavior and choice, product longevity, energy efficiency, and cleaner energy mix in reducing adverse environmental effects by being aware of the most significant categories, MAETP, FAETP, ADP-Fossil fuel, CC, and HTP, and minimizing negative environmental effects. According to the results of the study, transitioning to the 2035 electricity mix reduces all environmental consequences as compared to the 2022 electricity mix in Türkiye for dishwasher, washing machine, and refrigerator. Concrete reductions in environmental impacts have been determined when higher energy efficiency and fewer washing cycles were applied for washing machine and dishwasher within the range of reduction varying between 34 % - 36 % in all impact categories compared to the baseline scenario. The best scenario for refrigerator is energy efficiency with 2035 electricity mix in Türkiye by decreasing all impact categories by 20 %. Moreover, the steady decline in each of the impact categories demonstrates how effective energy efficiency is in lowering risks to the environment, public health, and non-renewable resources while simultaneously slowing down global warming. For the durability analysis up to 2053 when Türkiye aims to achieve net zero emissions of all selected appliances, the optimal scenario is renewing the appliances with the 20 % more energy-efficient one if it is desired to decrease the CC and ADP-Fossil fuel only. Otherwise, the best scenario is S4 if reducing all impact categories covering CC, FAETP, MAETP, ADP-Fossil fuel, and HTP without harming any environmental body is desired to achieve.

This study highlights the circular economy practices covering the production of electricity from cleaner energy sources, prolonging the lifespan of products with better service, supporting changes in consumer behavior, and increasing consumer awareness to prefer more environmentally friendly products in Türkiye up to 2053. Throughout the study, environmental benefits are compared for each scenario. While this study does not show any economic advantages from circular economy approaches like making appliances more durable through remanufacturing and improving repair services (including redesigning with easily removable parts to encourage repairs), as well as reducing

energy use, it can be stated that choosing energy-efficient and durable products can be economically advantageous in the long term. In addition, this analysis supports several legislations released under the EU Green Deal, Circular Economy Action Plan, promoting renewable energy resources, energy efficiency, and resources conservation through the life cycle of the product groups and helps Türkiye attain its 2053 net zero target. Furthermore, electricity mix analysis implemented through this study shows the decrease in current problem about energy resource dependency caused by providing some part of energy resources from other countries to Türkiye.

This study not only promotes circular economy and the documents provided in Table 4.1, but also supports SDGs aimed to be achieved by 2030. To illustrate, SDG 6 (on clean water and sanitation by ensuring sustainable water consumption and management), SDG 7 (on affordable and clean energy by supporting energy efficiency through product groups' life cycle), SDG 9 (on industry, innovation and infrastructure by encouraging sustainable industry), SDG 12 (on responsible consumption and production by urging energy-efficient and water saving production and consumption), SDG 13 (on climate action by mitigating the climate change effects), SDG 14 (on life below water), and SDG 15 (on life on land) are supported by pushing the utilization of sustainable resources, more durable, and energy-efficient appliances. Moreover, increasing LCA studies to achieve green transformation of the industry and to ensure sustainable growth in Türkiye was also mentioned in Green Deal Action Plan (2021) published by Turkish Ministry of Trade. Therefore, this study also complies with this strategy document of the Türkiye.

This study suggests using technological developments to extend the lifespan of appliances and improve the electricity generation mix with cleaner energy sources to make the world more sustainable. Energy efficiency labels which create communication between consumer and manufacturer play a key role in enhancing environmental performance of the appliances. Consumer behavior and choice options with their saving potential might also be written on the energy labels to increase public awareness. The government supports energy-efficient appliances and consumers might buy appliances with higher energy efficiency classes because of the technological enhancements providing economic advantages and environmental savings through less electricity consumption in the future use phase.

To conduct a deeper analysis of the environmental sustainability of selected household appliances, it is recommended that in future research, real data from the manufacture and disposal phases might be evaluated, consumer surveys might be carried out for the use phase to assess data as

machine program frequency, washing degree, number of the person in household, number of the place settings of the dishwasher, information about detergent, load ratio, prewash application, sensitivity analysis studies might be conducted in accordance with various programs in different temperature and duration, and cost analysis through life cycle to analyze the long term impact in Türkiye. Furthermore, it might be better to analyze the use phase for export of the product to non-environmentally friendly location in terms of electricity generation since electricity mix of the countries has a crucial impact on the environmental impact.

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