POTENTIAL ENVIRONMENTAL IMPACTS OF PLASTIC PACKAGING OF CONSUMER GOODS IN MEDITERRANEAN REGION

by

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POTENTIAL ENVIRONMENTAL IMPACTS OF PLASTIC PACKAGING OF CONSUMER GOODS IN MEDITERRANEAN REGION

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ABSTRACT

POTENTIAL ENVIRONMENTAL IMPACTS OF PLASTIC PACKAGING OF CONSUMER GOODS IN MEDITERRANEAN REGION

Synthetic plastics produced from non-renewable resources are widely utilized through its useful practices. Packaging is also an industry that highly consumes plastics around 44%, when other plastic industries are considered. The main polymer types, polyolefins, polystyrene, polyethylene-terephthalate, which are broadly used in consumer goods packaging involve single use plastics and cause damage on the environment including marine ecosystem. As impacts on the marine environment has also gained an extensive potential through Mediterranean Action Plan, main objective of this study is determined to assess potential environmental impacts of three plastic packaging materials in Turkey, Italy and Spain which represent nearly 14% of plastic pollution and 100 ton/day of plastic waste disposal in the region. Five environmental impact categories of climate change, acidification, resource depletion, ozone depletion, and photochemical ozone formation were studied to obtain results of packaging materials according to ReCiPe 2016 v1.1 and CML2001–Jan.2016 methodologies with GaBi 9.1.2 software. This study has shown that polypropylene material has had the highest environmental impact results in CML and ReCiPe methodologies due to fossil dependency. Moreover, scenarios with higher renewable energy share in their electricity grid, have received normalization results that have lower environmental impact. Packaging reduction targets set by European Commission were also lowered the environmental impact scores in the implemented scenarios. Climate change and resource depletion impact categories were obtained highest normalization scores among the five environmental impact categories. Also, scenarios with end-of-life options which includes higher recycling shares and lower incineration shares have taken lower environmental impact scores.

ÖZET

PLASTİK TÜKETİCİ ÜRÜNLERİ AMBALAJLARININ AKDENİZ BÖLGESİ'NDEKİ POTANSİYEL ÇEVRESEL ETKİLERİ

Yenilenebilir olmayan kaynaklardan üretilen sentetik plastiklerden kullanışlı uygulamaları ile genişçe faydalanılmaktadır. Ambalaj endüstrisi ise diğer plastik endüstrileri düşünüldüğünde plastiklerden %44 gibi büyük bir oranında faydalanan sektördür. Tüketici ürünleri ambalajlarında sıkça kullanılan ana polimer türleri olan poliolefinler, polistirenler, polietilen-tereftalatlar, tek kullanımlık plastikleri de kapsamakta, çevreye deniz ekosistemleriyle beraber zarar vermektedir. Deniz ortamındaki çevresel etkiler ise Akdeniz Eylem Planı ile büyüyen bir potansiyel kazandığından, bu çalışmanın amacı üç tüketici ürünleri ambalaj materyalinin potansiyel çevresel etkisini, üç Akdeniz ülkesi olan Türkiye, İtalya ve İspanya için değerlendirme olarak kararlaştırılmıştır. Bu üç ülke, UNEP istatistiklerine göre bölgede oluşan plastik kirliliğinin yaklaşık olarak %14'ünden ve yaklaşık 100 ton/gün miktarındaki plastik atığından sorumludur. İklim değişikliği, asitleşme, kaynak tüketimi, ozon tabakası incelmesi ve fotokimyasal ozon oluşumu şeklindeki beş çevresel etki kategorisi, plastik materyallerin sonuçlarını elde etmek amacıyla ReCiPe 2016 v1.1 ve CML2001–Jan.2016 metodolojilerine göre GaBi 9.1.2 yazılımı kullanılarak çalışılmıştır. Bu çalışma, polipropilen materyalinin fosil bağımlılığı ile ilişkili olarak ReCiPe ve CML metodolojilerinde en yüksek çevresel etki sonuçlarına varmış olduğunu göstermiştir. Dahası, elektrik enerjisi üretiminde yenilenebilir enerji payı yüksek olan elektrik şebekelerinin dahil edildiği senaryolar, daha düşük çevresel etki normalizasyon sonuçları elde etmiştir. Avrupa Komisyonu tarafından belirlenen ambalaj azaltma hedefleri dahil edilen senaryolarda yine çevresel etki sonuçlarını azaltmıştır. İklim değişikliği ve kaynak tüketimi etki kategorileri beş etki kategorisi arasında en yüksek normalizasyon skorlarını elde etmiştir. Ayrıca, yaşam-sonu seçeneklerinden yüksek geri-dönüşüm oranı ve düşük atık yakma oranına sahip olan senaryolar, daha düşük çevresel etki sonuçları almıştır.

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LIST OF SYMBOLS/ABBREVIATIONS

Symbol	Explanation
CFC-11 or R11	Trichlorofluoromethane
CO_2	Carbon dioxide
NO_x	Nitrogen oxide(s)
R	Radical group on a molecule
R'	Another radical group on the molecule
SO_2	Sulfur dioxide

Abbreviation	Explanation
ADP	Abiotic depletion
AP	Acidification potential
ES	Spain
EC	European Commission
GHG	Greenhouse gas
GWP	Global warming potential
H	Hierarchy
HDPE	High-density polyethylene
IT	Italy
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LLDPE	Linear low-density polyethylene
LDPE	Low-density polyethylene
MJ	Megajoule
MSW	Municipal solid waste
NEP	National Energy Plan
ODP	Ozone layer depletion
PE	Polyethylene
PET	Polyethylene-terephthalate
PO	Polyolefin

POCP	Photochemical ozone creation potential
PP	Polypropylene
PS	Polystyrene
PW	Plastic waste
SUP	Single-use plastic
TEİAŞ	Turkish Electricity Transmission Corporation
TPA	Terephthalic acid
TR	Turkey
VOC	Volatile organic compound
WTE	Waste to energy (energy recovery from waste)

1. INTRODUCTION

Nearly 98% of the traditional plastics manufactured are generated by monomers and substances received from the non-renewable petroleum reserves (Chawla et al., 2022). Utilization of non-renewable resource petroleum has found largest shares in three plastics markets; packaging by 44%, construction & building by 18% ratio, automotive by 8% and then, largest share of 44% in plastic packaging, which has obtained nearly all of its raw material from petroleum feedstocks, leaves non-degradable constituent to the environment at the end of their consumption (Vardar et al., 2022) (Plastics Europe, 2022). Annual plastic accumulation resulted in the environment is also identified greater than annually production of plastics, since plastic waste has non-degradable and accumulative characteristics (Pathak et al., 2023).

Considering the packaging plastics, the mostly used plastic polymers in packaging industry have become polyethylene-terephthalate (PET), polyolefins (polypropylene and polyethylene) and polystyrene (PS) (Kosior & Mitchell, 2020). It has been continuously of utmost importance to perform an analysis about environmental impacts of polymer types of PET, polyolefins, and polystyrene. Rather than other plastic materials with longer service life used in engineering and construction-building processes, the selected polymers above as packaging materials are frequently used and disposed (EuRIC, 2020). When the policies and role of plastic materials are considered, because of their key role in the production and consumption phases, European Commission has also put a remark about plastics and plastic packaging industries that highlights their significant roles in the Circular Economy Action Plan (2020). In a circular economy, there is a different approach for environmental protection rather than linear economy. So, specific plastic packaging waste recycling targets of 50%, 55% and 60% until 2025, 2030 and 2035 have been identified respectively, by European Commission in the circular economy approach (Callewaert et al., 2023). Efficiency of life cycle of a product is also important while environmentally friendly practices are supported for each life cycle phases (Nautiyal & Goel, 2021). For a linear economy in which plastics disposed when their service period ends and landfill or incineration practices are chosen, plastics lose its value by not applying practices of recycling, energy recovery or reuse. So, in a circular approach, sustainable development is remarkably encouraging in a perspective that embraces plastics, since their role is essential in a climate neutral economy along with their practical usage in climate friendly practices for needs of society such as wind power stations, electric cars, or energy efficient houses (Plastics Europe, 2022).

Environmental impacts on the marine and coastal areas have also emerged as remarkable concern to investigate through the Mediterranean Action Plan (MAP) and European Green Deal, and specifically the Mediterranean region has turned into an interesting region to study. Throughout the COP-22 goals, EU and countries around Mediterranean Sea had initiated attempts to protect sea-coastal environment around Mediterranean and to reach a healthy, clean, and sustainable Mediterranean Sea (European Commission, 2021). Accordingly, by utilizing life cycle assessment as a reliable tool to obtain environmental sustainability approach, it is possible to detect environmental impacts of plastics on a specific region. Life cycle assessment can analyse and correlate the impacts of various scenarios for processes or products. Furthermore, LCA quantifies and evaluates the potential environmental impacts of each life cycle stage of a product or service (Auras & Selke, 2023) . To quantify potential environmental impacts of activity or system, and it can also recognize the favourable circumstances to diminish the environmental impacts of the activity for the defined scope (Guo et al., 2023). By considering all the points above, the goal of this study is determined to assess environmental impacts of three selected plastic packaging materials of polyethylene-terephthalate, polyolefin group, and polystyrene used in consumer goods for three countries of Mediterranean Region with the aid of LCA methodology. While involving different scenarios, which are consisted of different electricity grids and different shares of end-of-life options such as incineration, landfill and recycling ratios, this study will be expected to provide a thorough understanding of potential environmental impacts for packaging materials in Turkey, Italy and Spain. In the study, scenarios with electricity grid data sets that contain higher share of renewable energy are supposed to have lower environmental impact scores. Also, among the three packaging materials, the packaging plastic which has less dependency on fossil fuels is thought to have less environmental impact score compared to the other packaging materials. Polypropylene packaging material has had the results that were highest environmental impact scores due to its fossil fuel dependency. Moreover, different shares of end-of-life options for different scenarios have also shaped the environmental impact scores of the results, the scenarios with higher recycling ratios have had the lower environmental impact scores.

2. LITERATURE REVIEW

2.1. Plastics

Plastics are synthetic materials commonly used related to its economic advantages, flexible features, and convenient practices in everyday life. In 2021, production number of plastics was 390.7 Mt in the world. Additionally, 90.2% of the global plastics production has supplied by fossil carbon sources including crude oil and natural gas, in 2021. Whereas the other 9.8% of total production has supplied by post-consumer recycled plastics in 8.3% and bio-based plastics in 1.5% (Plastics Europe, 2022). While bio-based plastics are obtained from renewable resources including biomass and some specific fossil fuels including polybutylene succinate (PBS), as a biodegradable aliphatic polyester that can consume by microorganisms; conventional carbon-based plastics consumes non-renewable resources (Emadian et al., 2017).

Production of extensive amount of plastic has arisen every year. Usage, diversity, and mass of the plastics have climbed enormously since 1950 from 1.5 Million tons; it had reached nearly 350 Million tons in 2017 without nylon and polyester as clothing fibers (Welden, 2020). In the EU, recycling and recovery rates are about 32.5% for plastic waste and the rest of the plastics finalize their end of life in the oceans or landfills (Chawla et al., 2022). Even though, there is enough precaution in common waste streams to prevent loss of plastic waste through collection and recycling methods; it is still observed 3.04 Mt amount of European post-consumer packaging waste sent to landfill in 2020 (Plastics Europe, 2022). Furthermore, due to persistent nature of plastic waste, these wastes have been able to accumulate and stay in the environment amount of 25 million tons per year (Tiwari et al., 2023).

Not all of plastics have gone through the recycling processes and the amount of plastic production become expanded recently; 1200 million metric tons of plastics is also believed to be present by 2050 in the environment or landfill areas (Welden, 2020). Accumulation and gathering of pollutants which are able to effect environment and health of human negatively explains pollution (Auras & Selke, 2023), thus plastics degrade at a too slow rate in these landfill areas, generates pollution as a serious problem for environment (Chawla et al., 2022). Additionally, for the degradation of plastic waste in landfill, study of Chamas et al. (2020) has investigated different environmental mediums of landfill (or soil), marine, biological degradation and sunlight exposure

and different plastic types of PET, HDPE, LDPE, PS and PP. In the study (2020), it was displayed that degradation of a plastic is correlated with the medium of plastic in which it degrades. Study (2020) was conducted a specific surface degradation rate (SSDR) value which covers estimating and extrapolating the half-life of plastics. The values of SSDR in the study have comprised a large scale because of different degradation in different environmental medium. For example, high-density polyethylene (HDPE) was associated with SSDR value of 0 to 10 μm/year in landfill, whereas the SSDR value has increased in marine environment to 0 to 30 μm/year. For low-density polyethylene (LDPE) has had a value of 1 to 100 μm/year in landfill, while SSDR value of polystyrene (PS) was 0 to 0.1 μm/year in landfill. For polypropylene (PP), the SSDR value was explained as 0 to 10 μm/year in landfill and SSDR value of PET was indicated as 0 to 0.1 μm/year in landfill, too (Chamas et al., 2020).

Primary disposal options for plastic wastes emerge as landfilling and incineration, however these conventional disposal options can lead to environmental problems. Landfilling conclusively provokes increasing of greenhouse gas emissions and causing leachate that able to harm soil environment and to produce toxic byproducts. Then, for incineration or uncompleted incineration processes, carbon dioxide emission becomes a persistent risk factor for environment. (Emadian et al., 2017; Kwon et al., 2023). In addition to these, incineration is known as having a potential to originate airborne microplastics and, microplastic particles can be transported to the aquatic environment by wind or be accumulated in the terrestrial environment (Akdogan & Guven, 2019). The microplastics are described as plastic particles in the size of 5 mm or smaller and, their sources are indicated as polyethylene, polypropylene, and polystyrene particles in medical or cosmetic products primarily. Its secondary source is characterized as plastic debris fragmentation caused by chemical, physical or biological processes (Akdogan & Guven, 2019).

Together with landfills and incineration plants, oceans also come out as final locations for mishandled plastic accumulation (Pathak et al., 2023). Ocean as an marine environment has been focused on due to increasing plastic accumulation and it is able to impact apparently oceans, wildlife, biodiversity and eventually, human health (Jambeck et al., 2015). Even though discharge of plastics from at-sea vessel is prohibited, 4.8 to 12.7 million metric tons of plastic waste is found entering oceans (Akdogan & Guven, 2019). Plastic debris, took place on coastlines, sea-surface level, in Arctic sea and sea floor, is identified all over the world and; oceans are especially found overwhelmed with the plastic debris (Gómez & Michel, 2013). Moreover, the UNEP data was indicated that 730 tonnes of plastic waste per day has polluted Mediterranean region (UNEP, 2024). Thus, the accumulation of these plastics emerge as primary plastic pollutants where ended up in

such places (Pathak et al., 2023). Mishandled plastic waste is detailed as insufficiently disposed or littered matter due to non-formal managing, open or uncontrolled landfill. Then, the mismanaged plastic waste is able to go into the ocean sooner or later by the way of wastewater outflows, wind transportation and inland waterways (Jambeck et al., 2015).

Plastic waste management is also a significant issue while production and consumption of plastics can damage ecosystem and wildlife. High production amounts of 380 million tons, 250 million tons of generated plastic waste and mismanaged global plastic waste production around 32% point out to handle plastic waste management properly (Castro-Amoedo et al., 2024). Even in European region, 3% of all plastic production ends up in the oceans, and able to damage marine habitat (Castro-Amoedo et al., 2024). It is also critical to reduce environmental contamination caused by plastics to valorize plastics in energy recovering practices and to provide no loss in the plastics value chain. Then, a suitable plastic waste management can be explained by providing both a sustainable environment and valorization of plastic material, while regarding efficiency. Recycling, thermal cracking (depolymerization), landfilling and incineration are traditional practices of plastic solid waste management (Elgarahy et al., 2023). However, whole traditional approach of plastic waste management has not given priority to sustainability approaches along with its landfilling and incineration practices. Thus, processes of mechanical and chemical recycling are considered more sustainable than traditional disposal approaches. Mechanical recycling can only perform in uncontaminated waste streams which are properly separated. (Elgarahy et al., 2023; Xayachak et al., 2023).

Plastic pollution is recognized as a remarkable global crisis that can create imbalance in ecological conditions. As a part of municipal solid waste, expanding number of single-use plastics (SUP) end up in landfills, in the drainage systems globally and eventually able to end up in oceans, too. Single-use plastics are seen as a considerable responsible for white pollution, defined as accumulation and leakage of plastics in the environment, since their usage has broadened to enormous amounts. Since most single-use plastics lack enough properties to be recovered appropriately under chemical, mechanical, or biological recycling after their consumption, and these SUP materials are also not manufactured by renewable resources that able to be biodegraded more probably, they have a substantial potential to impact environment (Auras & Selke, 2023; Emadian et al., 2017) The non-biodegradable characteristic of the petroleum-based plastics has been found responsible for plastic waste accumulation in the amount of millions of tons (Emadian et al., 2017). Plastic bottles and bags as single-use plastics are disposed more frequently when it is considered electronics or household appliances as other long-life goods (Welden, 2020). Service life-period of

plastic product also impacts whether plastic waste life end up in the environment or waste stream and, more than 50% of plastic packages are recognized with their very limited usage and short service-life period, before their disposal (Welden, 2020; Zhao et al., 2020). Thus, short service life of packaging materials can contribute pollution by ending up in the environment (Kosior & Mitchell, 2020).

Packaging industry with highest share of 44% in plastic applications, extracts the raw material from crude oil, and then, the refining process converts crude oil into petroleum products which can be a monomer for petrochemical feedstock. These monomers obtained from petrochemical feedstocks are the basic constituents of a plastic polymer that plastic packaging industry used (BPF, 2024). And in the plastic packaging industry, primarily three types of polymers are marked as polyethylene-terephthalate (PET), polyolefins (polypropylene - PP; polyethylene – PE; low-density polyethylene - LLPE; linear low-density polyethylene - LLLPE; high-density polyethylene - HDPE) and polystyrene (PS) (Kosior & Mitchell, 2020). These three types of polymers are also defined as thermoplastics, the polymers can be melted under heat or hardened under cold conditions and, solidity of the thermoplastics can be altered by applying cold or heat (Geyer, 2020). Thus, the thermoplastics become capable to be recycled for several times, even though certain types of these polymer types have proved to have insufficient recycling levels with 1% for PP and PS (Geyer, 2020; Letcher, 2020). For PET, HDPE and LDPE, the recycling levels are indicated higher around 19.5%, 10.3% and 5% respectively. Additionally, polypropylene and polystyrene are usually used for food packaging; PP is applied in the production of plastic bags and bottle caps; PS is utilized for plastic cutlery or cups, plates and expanded PS is for protective packaging and cups for hot drinks. HDPE is utilized in food packaging for milk products and cosmetic packaging for shampoo bottles, freezer bags, and LDPE is used for food packaging films with structure of film layers and plastic bags. Additionally PET, which is utilized to produce 110 billion beverage and water bottles each year, is processed in making of beverage and water bottles (Letcher, 2020). And most packaging materials are identified with not being sufficiently and efficiently recycled. Around 42% of plastic packaging waste material in EU sent to recycling (EuRIC, 2020) and for US, the recycling level is indicated as 9.5%. Moreover, 86% of the plastic packaging in the world is considered as never collected or sent to recycling (Letcher, 2020).

2.2. Crude Oil to Plastics

Crude oil and petroleum considered as fossil fuels since they are mixtures of hydrocarbons of remains from plants and animals that existed million years ago. Crude oil is separated into

petroleum products after its processing, and petroleum becomes a term that describes crude oil and petroleum products, too (EIA, 2024). Petroleum has become main feedstock for monomers since it has consisted of 95% to 98% of hydrocarbons, 2-5% nitrogen, oxygen and sulfur compounds. They have been largely aliphatic hydrocarbons, but it can change depending on its source of region. And polymer related industries, such as packaging material industry, has been indicated as a major customer for petrochemicals. Nearly about 60% of products of naphtha has been used in the processes to obtain polymers. The hydrocarbons in the crude oil have been cracked to olefin mixtures by previously performing the hydrocarbons under fractional distillation. (Wiley, 2016).

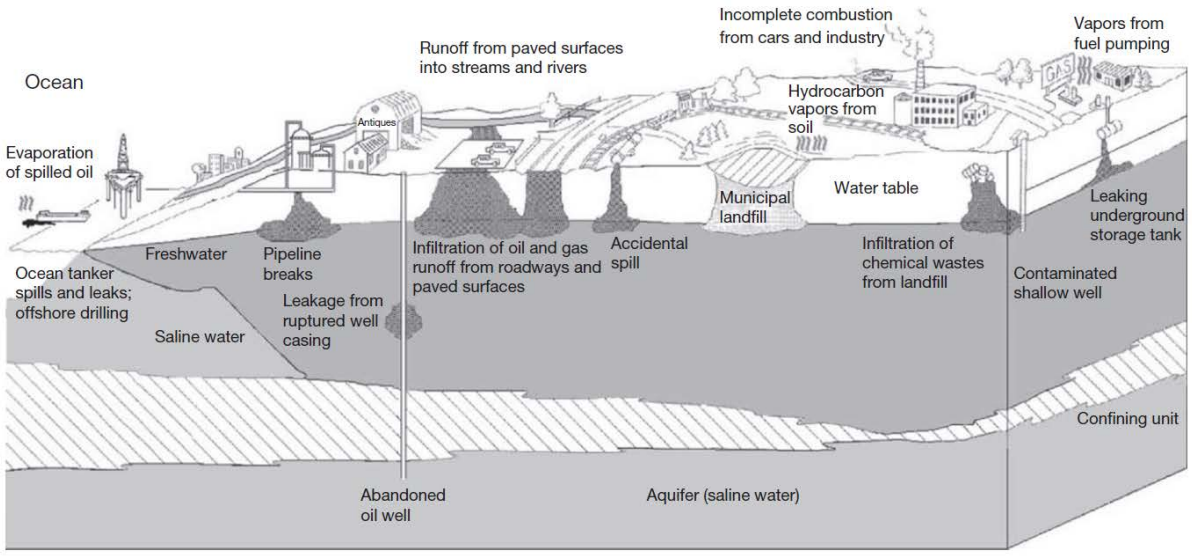

Figure 2.1. Contamination pathways of petroleum products while producing, transporting, use and disposing of it (Cozzarelli et al., 2014).

Since hydrocarbons and minor amounts of nitrogen, oxygen and sulfur are present in the mixture of petroleum resources, usage of petroleum in processes such as burning oil, combustion from industry and transportation can lead to release of atmospheric carbon dioxide and generation of emission. Its environmental and social impacts can stem from tanker ship accidents or usual activities of drilling, seismic exploration, and generation of waste, as it can be seen on the above figure of Figure 2.1 from the study of Cozzarelli et al. (2014). Utilization of subterranean and submarine reservoirs for crude oil extraction is an environmentally detrimental practice and have a potential to harm fragile ecosystems and human health. Pathways of human exposure from hydrocarbons have included ingestion, inhalation, direct contact or dermal absorption. In another figure of Figure 2.2 which is studied by Cozzarelli et al. (2014) again, exposure pathways of hydrocarbon contaminants is also can be observed. However, crude oil is a fundamental raw material for many industries in manufacturing processes, including synthetic fibers for clothing and

in plastics, synthetic rubber, paints, soaps, fertilizers, and insecticides. Then, an efficient use of carbon-based petroleum resources becomes necessary regarding environmental pollution (Cozzarelli et al., 2014; James G. Speight, 2017).

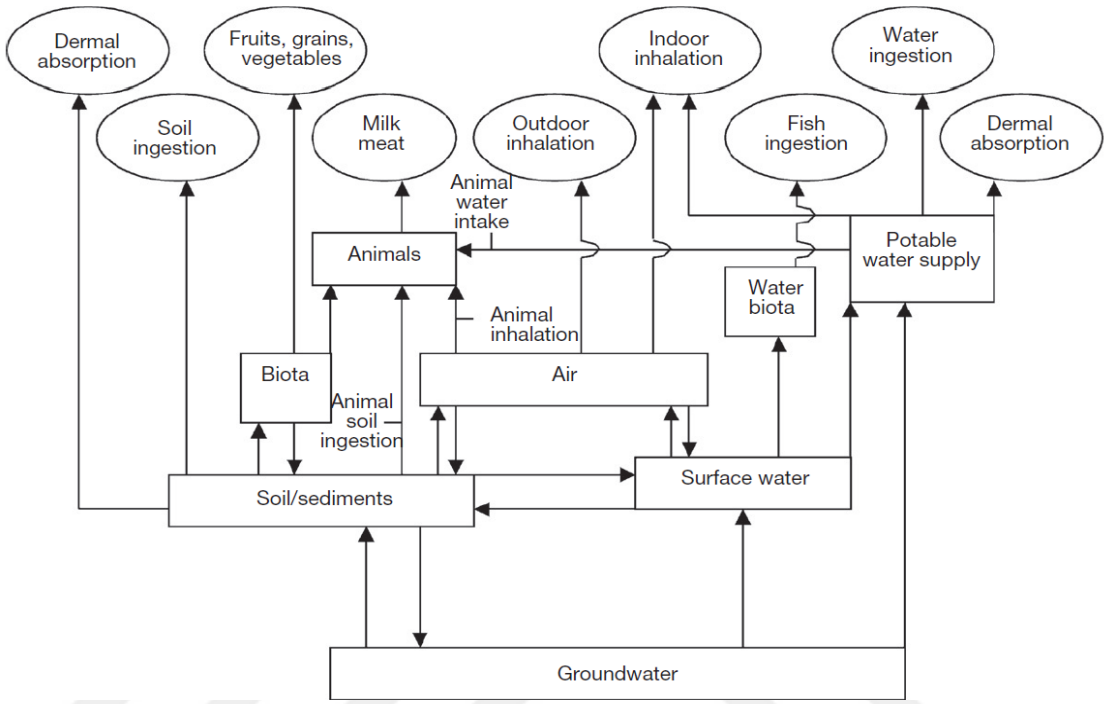

Figure 2.2. Exposure pathways of hydrocarbon contamination for human (Cozzarelli et al., 2014).

Crude oil has been found in reservoirs as a subsurface medium for collection of trapped hydrocarbons in the fractured or porous rock structures. Natural gas can also be obtained with petroleum as a gas cap, according to Speight (2011). Most of the crude oils that are recovered has been obtained from the underground reservoirs. Crude oil products such as gasoline, kerosene, diesel fuel, fuel oil and petrochemical feedstocks such as ethylene, propylene or butene are obtained in refineries by converting crude oil. Refinery processes of crude oil have been separated into three categories which are processes of separation, conversion and finishing. Separation process has been indicated as distillation, conversion process has been indicated as catalytic cracking and coking, and finishing process was exemplified as hydrotreating of material to remove sulfur content. Topping refinery has been the simplest form of refinery, and it has performed to prepare feedstocks for production of industrial fuels and petrochemical manufacturing. Conversion refinery has been the most useful refinery for today, since it has had many practices of gas oil conversion as catalytic cracking, polymerization units as olefin conversion plants, coking units as reducing residual fuel amount. Conversion refinery has been also able to recover propylene, benzene, toluene and xylenes

in its further processes. These processes and their products can be seen on the below, Table 2.1 (Speight, 2011; J. G. Speight, 2017).

Table 2.1. Production of materials for petrochemical processes (J. G. Speight, 2017).

Starting Feedstock	**Process**	**Product**
Petroleum	Distillation	Light ends Methane Ethane Propane Butane
	Catalytic Cracking	Ethylene Propylene Butylenes Higher olefins
	Coking	Ethylene Propylene Butylenes Higher olefins
Natural gas	Refining/gas processing	Methane Ethane Propane Butane

Refining crude oil has generally indicated the separation of the crude oil constituents to different useful products. These crude oil products can be converted to other saleable manufactured products via additional processes. Refining of crude oil involves separating the crude oil into different fractions regarding their different boiling point ranges by distillation processes. Boiling point range of 1 – 205 °C (32 – 40 °F) is the lowest boiling range, and the products of the boiling range are naphtha and gasoline, which are used in the petrochemical industry. These are hydrocarbons that contain four to nine carbon atoms and can be named as light and heavy naphtha fraction. Second boiling point range of middle distillates in between 205 – 345 °C generates kerosene, diesel fuel, jet fuel and heating oil. Other two boiling point ranges for distillation of crude oil are in between 345 – 565 °C and 565 °C and above. These products are heavier distillates, have 20+ carbon atoms and give the products of gasoil (wax and lube oil) and residuum, respectively (James G. Speight, 2017).

Naphtha product of the lowest boiling point range in crude oil distillation process is utilized for petrochemical industry as a feedstock. Naphtha is an immensely used and essential compound to make polymers (BPF, 2024). Products of petroleum refinery as naphtha are processed to polymers that can be turned into plastics by further processes. Olefins (ethylene or ethene and propene or propylene) and aromatic derivatives (benzene, toluene, xylene isomers) obtained from naphtha are

vastly used petrochemicals that derived from crude oil (James G. Speight, 2017). The process that aims the production of olefins from a stream of light hydrocarbons such as naphtha, and then diluted the naphtha with steam and heated in furnace without oxygen is called steam cracking. Steam cracking applied to naphtha is a useful and greatly used petrochemical process to get basic constituent of polymers that used in plastic packaging, such as polyolefins, polyethylene-terephthalate and polystyrene (Posch, 2011). Flowchart of monomer formations has also been shown on the figures of Figure 2.3 and Figure 2.4.

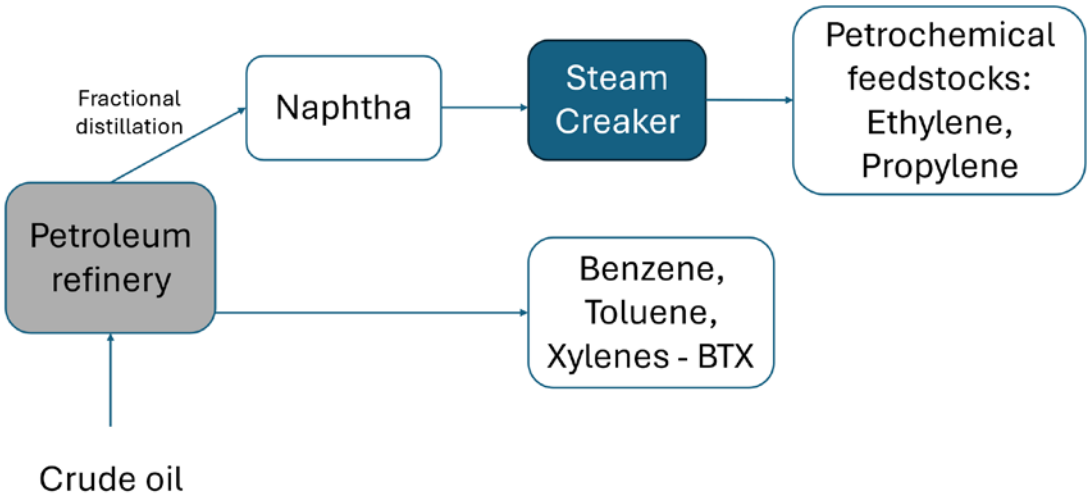

Figure 2.3. Crude oil to petrochemical feedstocks - polymer monomers.

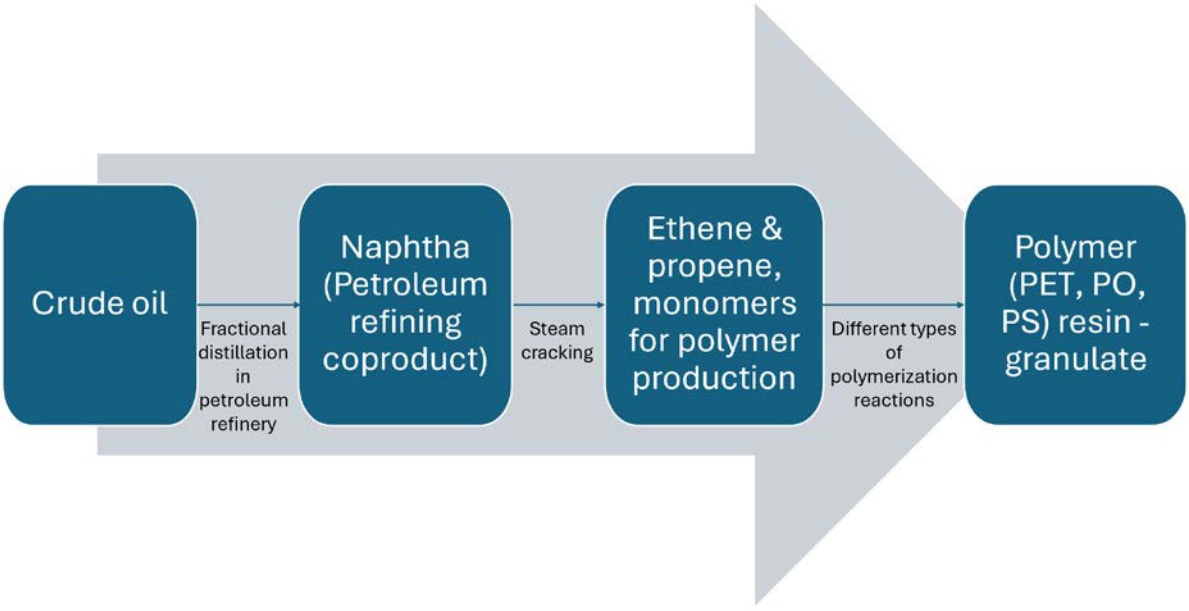

Figure 2.4. Basic scheme of crude oil to polymer compounds.

Polyolefins are polymers that produced from alkene groups as monomers. Alkene is an unsaturated hydrocarbon molecule including double bond, and the double bond in the monomer have a potential to synthesize polymer with the chemical reactions. Hydrocarbons of ethene and propene with lower carbon number are able to produce longer hydrocarbon bonds and high carbon molecules (Posch, 2011). Ethene and propene as a source of polyolefins can be obtained from steam cracking of crude oil, which converts high hydrocarbon molecules into smaller hydrocarbons (light hydrocarbons). A saturated hydrocarbon molecule in the cracking process, as naphtha, is converted into smaller and unsaturated hydrocarbons. Unsaturated hydrocarbons are hydrocarbons that containing at least one carbon to carbon double bond. And this process becomes an essential industrial method to produce low carbon molecules which are ethene ($CH_2 = CH_2$) and propene ($CH_3 - CH = CH_2$). In steam cracking, gaseous or liquid hydrocarbon feed as naphtha, ethane, or low-pressure gas (LPG), diluted with steam then heated for a very short period in a furnace without oxygen. Very hot reaction temperature around 850 °C is reached in the furnace, and the gas in the medium rapidly cooled down to stop the reaction. The products of the reaction also rely on what is put in the feed, amount of steam density and degree of cracking temperature. Light hydrocarbon (light naphtha, ethane, LPG) feeds can generate products of lighter alkenes with low carbon numbers which are ethylene and propylene. And heavy naphtha feeds can produce these light alkenes with other aromatic hydrocarbons, too (Posch, 2011).

For polypropylene, it is known as a homopolymer that have repeating subunits, similar to PE. These repeating subunits have been generally obtained from monomers (Figure 2.5, Figure 2.6). To obtain polyethylene and polypropylene, addition or chain polymerization mechanism are utilized (Selke & Culter, 2016). Especially, metal-catalyzed polymerization reactions are performed in order to get large volume of polyethylene and polypropylene. Transition metal alkyls are used in the reactions of metal-catalyzed chain polymerization reaction. Principles in this polymerization type have been the same as conventional polymerization steps which are steps of initiation, propagation, chain transfer and termination (Hillmyer, 2012).

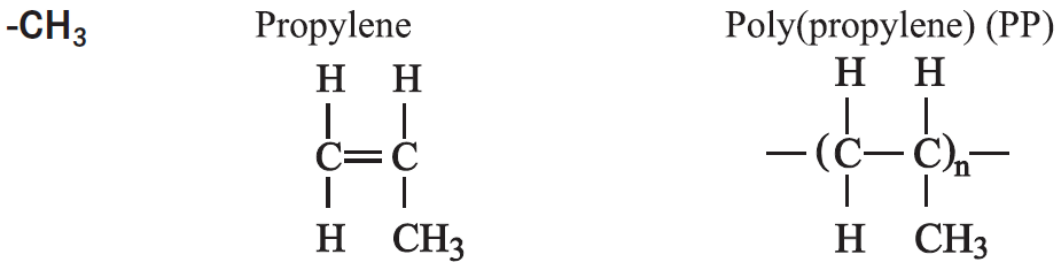

Figure 2.5. Monomer and polymer of polypropylene (Selke & Culter, 2016).

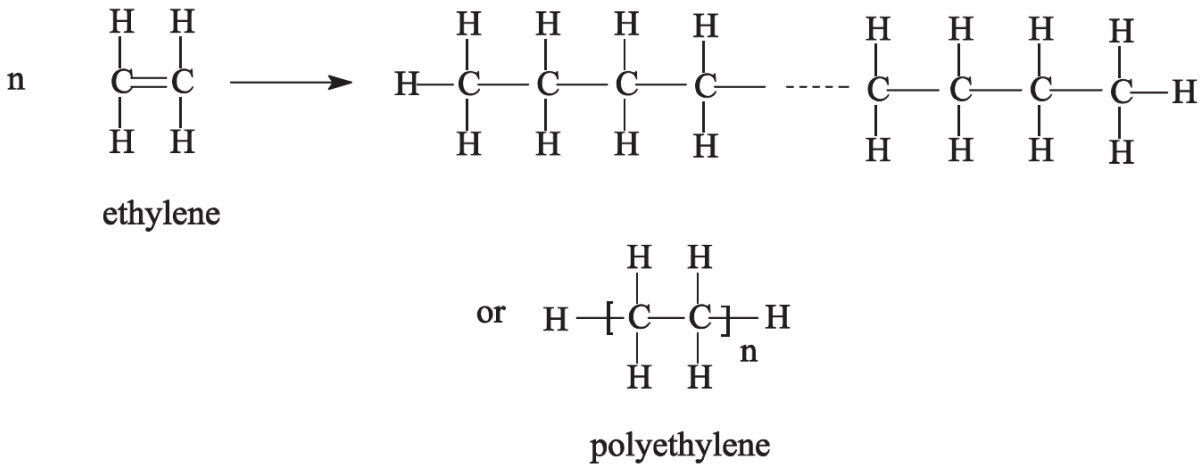

Figure 2.6. Polymerization of ethylene monomer via free-radical polymerization mechanism, n is the number of monomers (Selke & Culter, 2016).

For the of addition polymers of polyethylene, polypropylene and polystyrene, conventional polymerization steps that can be associated with free-radical polymerization are followed. A free radical that includes unpaired electron and obtained from a reaction or decomposition of a molecule. These radicals are indicated as energetic molecular fragments that are able to give reaction easily since they have an unpaired electron. In this case, they are able to react with double bond of C = C, which is present in the considered monomers of ethylene, propylene or styrene. These radical fragments are led monomers to create a free electron ending and then, growing chain can be generated via a larger free ending monomer. Initiation that has two steps of free radical formation and reacting the free radical monomer to get a free ending. Initiators have been unstable compounds relative to the monomers, these are indicated as a peroxide (R-O-O-R') compound, a hydroperoxide (R-O-O-H) compound or an azo compound (R-N=N-R') that contains nitrogen double bonding instead of O-O bond, in the study of Selke & Culter (2016). High temperature or ultraviolet (UV) radiation have been also correlated with free radical generation. As can be seen on Figure 2.7, free radical ending in monomer is obtained by the incorporation of free radical and monomer, and then chain is started to grow. In propagation step, monomers are added from the free radical ending, double bond on the monomer is broken and a larger chain with free radical ending is obtained, continuously. For the step of termination, polymerization reaction is required to be ended. One of the termination mechanisms is shown on the figure of Figure 2.7, two larger chain of free ending radicals are reacted, and the polymerization can be ended according to the study of Selke & Culter (2016).

After polymers of PE obtained by polymerization reactions, molding methods of extrusion coating, blow molding and injection molding are used to obtain manufacturing processes of PE as packaging materials. Molding plays a significant role in plastic processes to shape the plastics. The molding methods handle liquid plastics within a mold or container, then any plastic can be hardened regarding the desired shape with the aid of shaping operations. These molds include a solid block and cavities in which plastics get shaped in (Cantor & Watts, 2011). Similar to other packaging materials, PE and PP materials are usually applied injection molding process. As can be seen on Figure 2.8, PP material was mostly applied under the process of injection molding. This molding process is indicated as a widely used process for packaging materials, according to the Wiley's book (Wiley, 2016). For injection molding, which practiced under pressure, the melted polymer is injected directly into mold. The process of injection molding is known as a functional processing method to handle hot melted PE. For manufacturing processes of closures and caps of bottles, containers, and many other materials, injection molding becomes applicable Blow molding can be used for producing hollow objects such as bottles and containers for packaging. While a melted plastic is put into the mold, a gas mainly air is used through the hole to obtain the shape of the mold. Extrusion coating is applied for the manufacturing of flexible packaging. Then different polymers can be combined or coated on PE to obtain sufficient performance or aesthetical standards for final material (Jeremic, 2014).

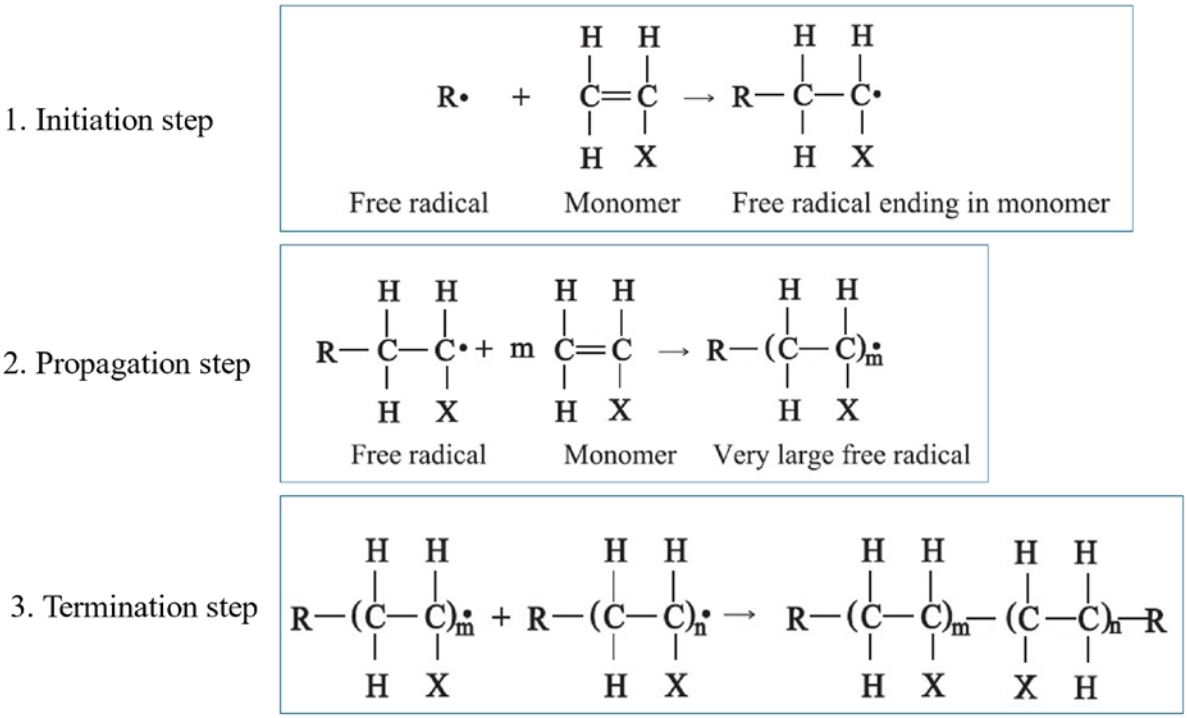

Figure 2.7. Free-radical polymerization mechanism held by addition polymers, acceptable mechanism for PE, PP, PS (Selke & Culter, 2016).

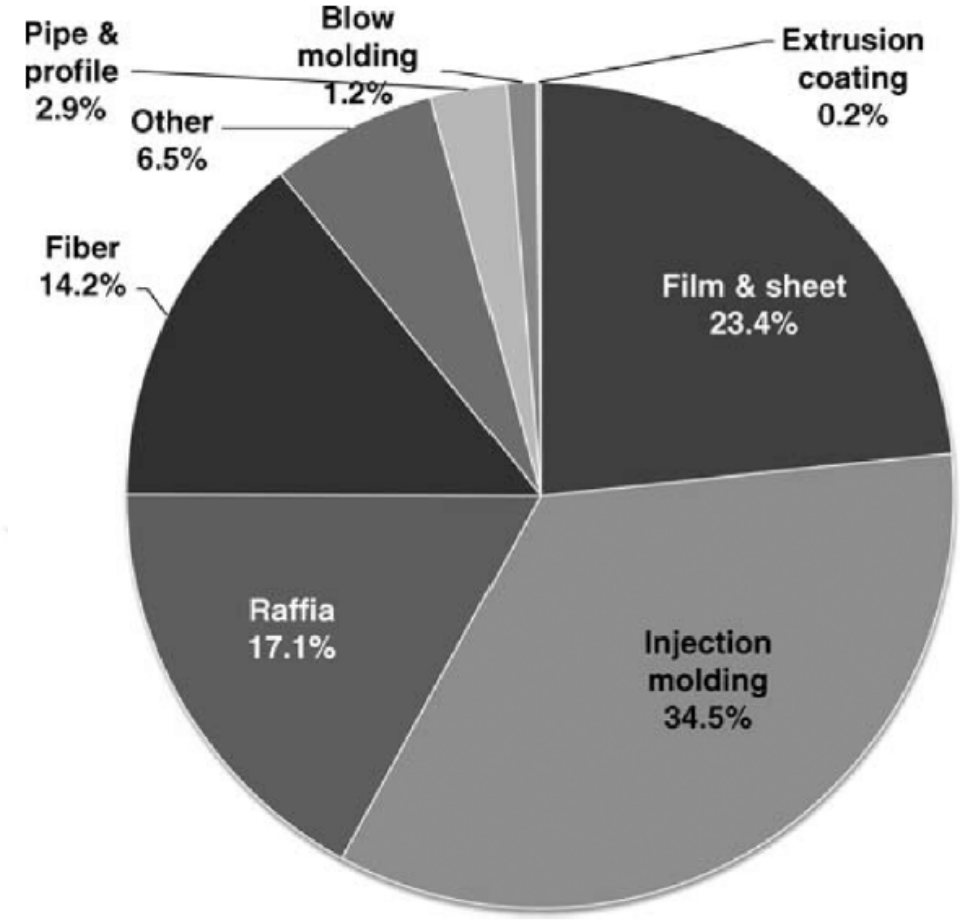

Figure 2.8. Polypropylene plastic material, molding applications (Wiley, 2016).

However, when the environmental issues are considered, it is seen that polyethylene and polypropylene become directly petroleum related plastic packaging materials as it is mentioned earlier. Utilization of petroleum resources has a potential to negatively impact the environment, while production, transportation and exploration of petroleum resources are considered. Drilling and exploration activities can create harm on the marine environment, too. Oil spills have potential of other detrimental impacts originated by accidents on the ships, pipelines or trains and truck on the land. Oil spills can also heavily contaminate the water and soil ecosystem, and generates fires or explosions (EIA, 2024). The production stages of polyolefins are also able to create damaging environmental impacts such as releasing of inert waste to landfill, hazardous waste, and creating the emissions of VOC (volatile organic compounds) and COD (European Commission, 2007).

Raw material of polystyrene as another thermoplastic is styrene molecule including a benzene ring ($C_6H_5 - CH = CH_2$). The benzene ring makes polymerization of styrene molecule achievable to obtain polystyrene by performing not only one but more than one type of polymerization

pathway. However, industrial polymerization of styrene is practiced mostly via free radical polymerization mechanism (Figure 2.7) which is the general mechanism of addition (chain) polymers similar to polyethylene and polypropylene (Hillmyer, 2012).

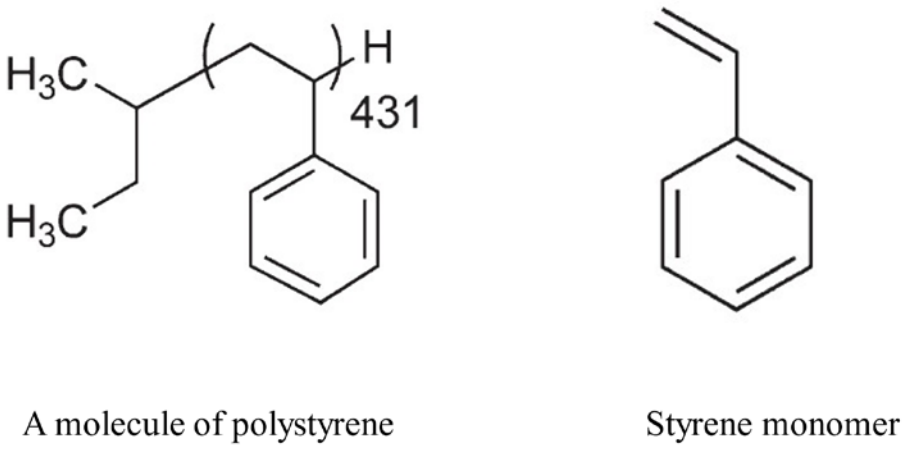

Figure 2.9. Polymer of polystyrene and monomer of styrene (Hillmyer, 2012).

Styrene itself can begin the polymerization reaction without any additional initiators with the aid of electrons on its ring. At first, styrene molecule is heated to obtain its free radicals. These radicals can proceed further polymerization reaction, then the radicals on the reaction medium become ready for next steps of polymerization. Excess monomers of styrene are added end of the styrene chain and then a polymer chain is produced. Length of polymer chain is controlled by reaction temperature, specific chain transfer agent and initiators. Another method of polymerization for PS production such as cationic polymerization gives small amount of mass polystyrene, so the other types of polymerizations are not highly efficient methods for industrial practices. (Maul et al., 2007). There have been also many ways to polymerize styrene molecule. By anionic chain polymerization of styrene, which follows the steps of free-radical polymerization mechanism (Figure 2.7), a free radical molecule as carbanion of butyl lithium can also lead to an initiation step while reacting with styrene monomer as can be seen on below simple mechanism figure (Figure 2.10). Carbanion is a molecule which containing a unsaturated Carbon atom, with a negative charge. Termination step has become avoidable by non-presence of acidic compounds, which can be led by methanol molecule (H-O-CH_3) (Hillmyer, 2012). Through an environmental approach, all these manufacturing processes of general-purpose polystyrene have been associated with the inputs the such as energy, process water and; outputs such as air - water emissions, VOC emissions, wastewater, COD and BOD emissions on water. These inputs and outputs should also be considered

while heavily industrial production of this packaging material is maintaining (European Commission, 2007).

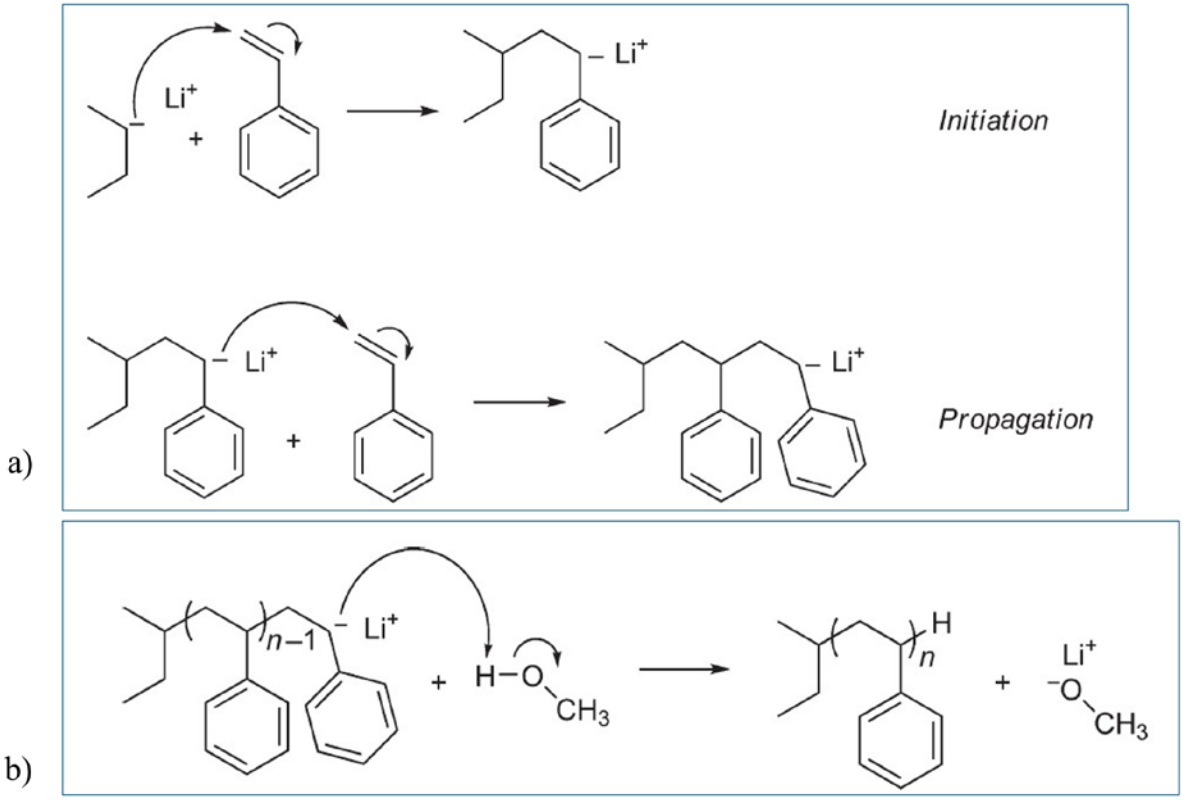

Figure 2.10. a) Mechanism of PS initiation step via butyl lithium on above and propagation step via carbanion attacking to styrene monomer on below, b) PS termination by methanol (Hillmyer, 2012).

Polyethylene-terephthalate, known as PET, is a thermoplastic that produced via polycondensation (step condensation polymerization) reaction of ethylene glycol molecule (OH - CH_2 – CH_2 - OH) and terephthalic acid (TPA) molecule ($C_6H_4(CO_2H)_2$) by adding specific catalysts such as zinc, calcium and manganese acetates (Gubbels et al., 2018; Hillmyer, 2012). Polycondensation, also known as step-growth polymerization, is a process that forms byproducts (water) through the polymerization and links the monomers in two steps of condensation, then polymerization, as can be seen on Figure 2.11. Monomers containing heteroatoms such as ethylene-terephthalate undergoes polycondensation reactions (Gubbels et al., 2018). After polycondensation is carried out with high temperatures, obtained PET can be processed by using molding methods such as injection molding, blown molding and extrusion (Sin & Tueen, 2023). Different molding methods are applicable for different types of polymers, but method of injection molding is known as an extensively practiced processing operation for production of PET plastics (Cantor & Watts, 2011). Although production processes have enough practical capabilities to be sufficient for

industrial activities, processes of heavy PET production also have environmental burdens within an environmental aspect. A plant that carries out PET production processes can generate hazardous waste, non-soluble polymer waste and wastewater. Polycondensation process based on TPA, post-condensation processes and PET processing consumes energy and water at high amounts, too. These whole processes of PET production also bring environment outputs of VOC, COD emissions (European Commission, 2007).

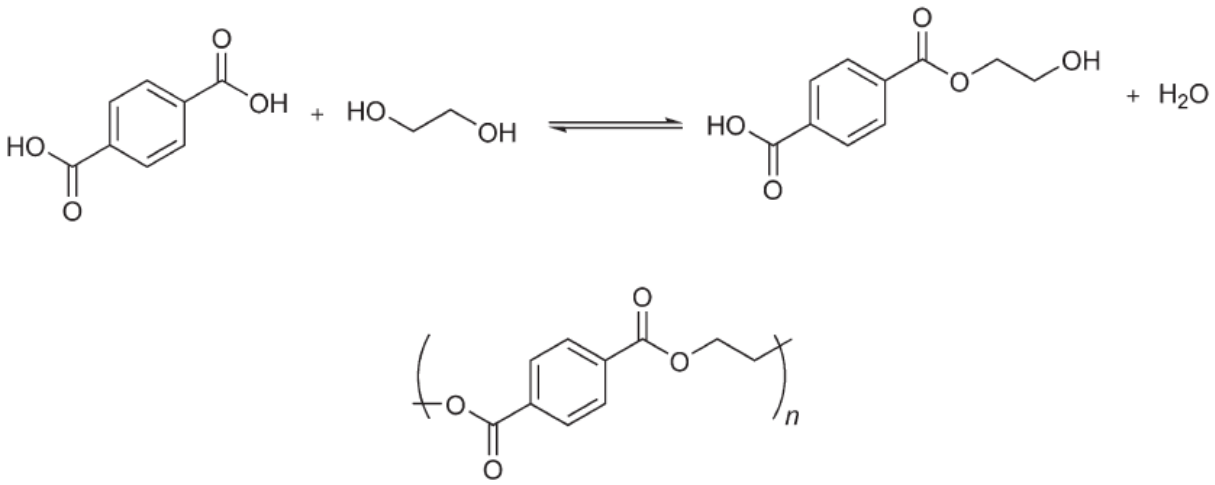

Figure 2.11. Basic figure of condensation step of ethylene glycol (OH - CH_2 – CH_2 - OH) and terephthalic acid ($C_6H_4(CO_2H)_2$) on above, polymerized PET on below (Hillmyer, 2012).

2.3. Life Cycle Assessment & Plastics

Life cycle assessment has appeared as a useful evaluation method to quantify environmental impacts of any process, system, or product by assessing inputs and outputs for the evaluated activity. For the environmental impact of recycling and recovery scenarios of three plastic packaging material, there are various LCA studies that manages this comparison in different scenarios within the aspect of circularity of plastic industry. Different end-of-life options for specific packaging materials through performing LCA has been identified in the literature. Likewise, some part of LCA studies had focused only one packaging material and evaluated its environmental impact among different end-of-life scenarios. And some articles have investigated different packaging materials and compared their impacts, while some others have examined most efficient recovery scenarios for these packaging materials. Initially, the article of Bassi et al., (2022), has assessed environmental impacts of EU demand for polyethylene-terephthalate packaging and quantified the impacts through life cycle assessment, from 2020 to 2030 (Andreasi Bassi et al., 2022). Bassi et al. have observed that societal and environmental savings can become possible by changing the waste management. Through setting eight different waste management

alternatives, the study (2022) has examined to compare alternative PET packaging scenarios with Business-As-Usual scenario as current practice. Starting from 2020 to 2030, a cumulative demand of plastics was calculated as 63 Mt in the EU, which sends 26 Mt to recycling and 8.5 Mt to deposit-refund systems. So, a 36 Mt amount of plastic waste in the Business-As-Usual scenario has been expected to end up in mixed waste, which has become a challenge for circular economy approach. PET packaging in the study (2022) was studied under five sub-category of clear bottles, colored bottles, flexible packaging, strapping and trays. The eight waste management alternatives in the study have been “high collection rate for bottles” by including deposit systems and increasing the collection of bottles via deposit 100% for 2029; “high collection rate for trays” by increasing the collection rates of trays; “high sorting and plant recycling rates” by enhancing the sorting rate of trays and bottles, and increasing the recycling rates in the EU countries; “100% to fibers” by excluding need of secondary markets in the PET packaging and inducing open-loop recycling; “100% to strict closed-loop” by including recycled secondary PET compound in the PET packaging market again. Alternative VI and VII have been defined as “improved systems with open and closed loop recycling” by combining improvement on collection – recycling rate and open-closed loop recycling methods; and lastly alternative VIII “the linear system for PET packaging” by excluding all recycling systems as it was before 2000.

With the result of life cycle assessment, saved amounts were revealed as 38 Mt of CO_2-eq and 34 kt of $PM_{2.5}$-eq for alternative VII which has been included improvements on recycling, sorting, collection rates and closed-loop recycling system which requires the secondary PET and does not export the PET bale outside of EU. Alternative VII has also been found as refining additional 9.4 Mt of oil and 2.3 Mt of natural gas, by not consuming fossil resources and reducing the fossil-dependency on PET packaging production when it was compared with Business-As-Usual scenario. Alternative VII in 2030 has had a potential to get 50% reduction in the consumption of fossil fuels with improved recycling, sorting and utilization of secondary PET material for the year 2030 and 35% reduction for cumulative period of 2020-2030. Climate change was computed in CO_2-eq and particulate matter formation was computed in $PM_{2.5}$-eq in the article of Bassi et al. These two environmental impact categories were found more applicable among the 22 impact categories recommended in ReCiPe 2016, which is a method to calculates impact scores from life cycle inventories. Moreover, results of climate change and particulate matter formation impact categories have demonstrated that recycling of PET material has been more efficient than landfilling or incineration operations. Among different waste management alternatives examined for future, linear system for PET packaging, has led to an added amount of 55 Mt of CO_2-eq and 37 kt of $PM_{2.5}$-eq due to loss of recycling potential. Linear system (explained as Alternative VIII in the study) has

been defined as an alternative that does not include any recycling system and disposes mixed waste without separate collection method, also sends the waste to landfill or incineration facilities. This alternative of end-of-life options has shown a total failure in recycling within waste management systems. In the article (2022), societal costs were also calculated in terms of net job creation or loss. For improvements performed in the alternatives, authors have added jobs related to sorting, recycling and collection. Jobs related to landfill and incineration processes have been decreased by authors. Then, alternative VII as a combination of improvements, has been demonstrated with its new job creation potential in between 158000 to 168000. To perform a totally linear system as in alternative VIII, has been marked with a problem of job reduction (loss of 173000 jobs) by removing jobs related to recycling, when Business-As-Usual practices was considered. Thus, without an improvement in the waste management techniques, the environmental impact results in ReCiPe method obtained via LCA studies, have been increased (Andreasi Bassi et al., 2022).

ReCiPe and CML are LCIA methodologies that transform results of life cycle inventory to potential environmental impacts with their different characterization factors. These two LCIA methodologies are mostly used in the LCA studies (Torkayesh et al., 2022). CML methodology is grounded on midpoint modelling, and it handles to operationalize standards of ISO 14040. ReCiPe methodology uses midpoint and endpoint characterization factors. These two levels of characterization factors are aligned in a cause-effect chain for environmental problems (European Commission, 2010). At the midpoint level, the characterization factors have the location that stands after the emission flow, in between the cause and impact chain. Midpoint level characterizations were indicated as having a lower uncertainty for parameters and closer relation with environmental flows. For the endpoint level, characterization factors indicate the damage at the areas of protection, which are human health, resource scarcity and ecosystem quality. And the endpoint level characterization factors are able to explain clearly environmental relevance of the environmental flows (Huijbregts et al., 2017). Furthermore, for ReCiPe methodology, there have been symbols such as (H), (E), and (I) on the midpoint and endpoint indicators. These have indicated as hierarchist perspective (H), egalitarian perspective (E), and individualist perspective (I) which are different value choices, and each one symbolizes different reliabilities. (I) has an optimistic perspective that indicates humans are adaptive via technological developments and can avoid the environmental problems; egalitarian is longer term-decision based perspective that can give worst case results, believes nature is not stable and sensitive. Hierarchist is in between these two value choices, not that optimistic nor that pessimistic, it signifies impacts on environment can be prevented via convenient management of waste (De Schryver et al., 2013).

According to study of Tiwari et al. (2023), recycling processes has been remarked in a way that provides less energy usage, having a potential to minimize pollution on the ecosystem and leading protection of environment (Tiwari et al., 2023). Practice of recycling has included turning waste items to more useful goods. This practice has also known for its reduced amount of CO_2 emission when it is considered conventional technologies for plastic waste management which are incineration and landfill processes. Even though incineration processes have had the potential of reducing amount of waste by burning it at high temperature and generating energy by recovering non-biodegradable waste, this process can pollute environment while burning plastic waste and releasing gases of CO_2 and water vapor and harmful ashes. Its set-up has been also found costly. Landfill sites have also had a potential to pollute environment by holding toxic chemicals of dioxins, furans and hydrocarbons. Bioremediation has also exemplified as a process in conventional plastic waste management, but their practices have also been costly while providing required enzymes in order to biodegrade the plastic material. Its practice has also been sensitive when the environment of bioremediation includes biological inhibitors.

As Tiwari et al. (2023) had highlighted, the conventional plastic waste technologies have not been entirely clear, not-harmful technologies. The conventional recycling technologies shown in the article have been associated with having a potential to harm environment in aquatic, terrestrial, atmospheric lands, cause large amount of GHG emissions. And when it comes to recent technologies of plastic waste management, sorting of plastic waste has been essential for mechanical and chemical recycling, according to the study (2023). By sorting the PW, recycling processes can become faster, and cost-rate of plastic waste can be maximized. In the study, practices of sorting and reprocessing were defined under mechanical recycling. While separating the plastics with respect to their chemical properties, plastics have become isolated from impurities for mechanical recycling. After these steps, by involving melting and shredding processes, further processes of recycling can be applied. Techniques of pyrolysis and liquefaction have been described in the study as efficient techniques by recovering energy and producing high value secondary products of fuel and char. Plastic to fuel technologies have been the technologies that are able to reduce the dependency on fossil fuels. However, these have been expensive technologies and contaminants in the plastic waste stream can create challenges for the mechanism of these processes. Recycling PW was also marked to have a potential to solve landfill disposal problems by Tiwari and coworkers (Tiwari et al., 2023).

Another article on the relationship of LCA and plastics was written by Ingrao and Wojnarowska (2023), to evaluate environmental impacts of the PET bottle production for packaging

(Ingrao & Wojnarowska, 2023). In the LCA study, the system boundaries were set in a way that includes significant steps in life cycle of bottles. These steps examined in the LCA study have been PET granulate production, blow-moulding for PET-body preparation, and end-of-life scenarios. Distribution of the PET-bottle packed beverage and post-blowing processes phases (filling to shrink wrapping) were excluded from system boundaries in the study of Ingrao and Wojnarowska (2023). Functional unit for the study was chosen as "1 kg of produced PET body". Then, post-consumer PET bottles which sent to landfilling, recycling and municipal incineration in Italy with different shares of 10.1%, 45.5% and 44.4%, respectively. For Italy, PET and PE bottles, PP packaging materials, PE packaging films have been found to send these facilities, according to the article (2023). The impact categories in the LCA study were set according to inputs as consumed energy resources, materials, and outputs as emissions in water, soil, air obtained via Life Cycle Inventory (LCI). Then, the impact categories in midpoint step were computed as damage categories which is indicated as endpoint step (Figure 2.12.). The endpoint step has been practiced in order to involve comparison phases of "normalization" and "weighting". Midpoint impact categories in the study were selected as global warming with reference unit of "CO_2-eq", respiratory inorganics with reference unit of $PM_{2.5}$ and, non-renewable energy with reference unit of "MJ" by expressing impact results in these categories. Human health, climate change, resources and ecosystem quality have been the endpoint damage categories.

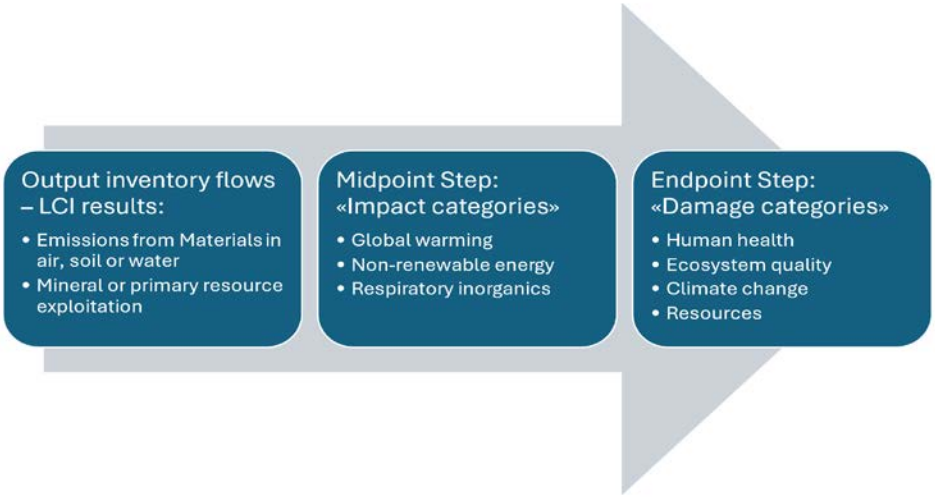

Figure 2.12. Basic LCIA framework in the study of Ingrao & Wojnarowska (Ingrao & Wojnarowska, 2023).

According to the article (2023), the single score evaluation of "Resources" damage category has been found highest on the stage of "PET granulate production", and "human health" damage

category result has been the highest one among the damage categories on the stage of “processing into PET bottles”. For post-consumed bottle recycling, environmental benefits of this stage were pointed in the study and damage category of “resources” has had the highest single score related to environmental benefits. Shortly, the highest environmental impact result was found in the stage of “PET granulate production” and, the life cycle stage that had highest environmental benefit has become “recycling of post-use bottles” with a percentage of 31% by sending 45.5% of consumed PET bottles to recycling in Italy. Smaller contributions of environmental impact have been also counted in the stages of landfill and incineration processes of post-consumed bottle, while the processing stage of PET bottle was contributing 38% in the total environmental impact. In the study, it was also emphasized that replacing 50% of virgin PET usage with recycled PET has been found to generate a valuable benefit potential on the environmental impacts, when these two different scenarios of PET bottle life cycles were compared. Environmental benefits can be obtained with secondary raw materials that acquired from recycling processes. And, in the study of Ingrao and Wojnarowska (2023), it was demonstrated with recycled PET, yet secondary raw material qualifications were indicated as questionable. However, partial or fully usage of recycled PET were found not totally lowering the quality of the bottles, and it has made the recycled PETs having a noteworthy potential. With the study, it has been also investigated that circularity of post-consumed PET bottles by combining closed-loop recycling applications. Recycled and pre-produced PET granulates have also had a potential for being a raw material and utilizing in processing stage of PET bottles (Ingrao & Wojnarowska, 2023).

In the study of Lange (2021), end of life opportunities and challenges for plastic waste were examined through the life cycle assessments (Lange, 2021). Similarly, Lange (2021) has found performance of recycling is effective in terms of GHG emission savings when it is considered incineration as an energy recovery method. However, it was spotted that GHG savings of recycling disappeared when a successful carbon sequestration has been accordingly performed with landfilling. For polyolefins, it has been pointed out that CO_2 benefits were found least in the incineration, and less in the chemical recycling processes of gasification and pyrolysis. CO_2 benefits were highest in the mechanical recycling for PO, too (Figure 2.13).

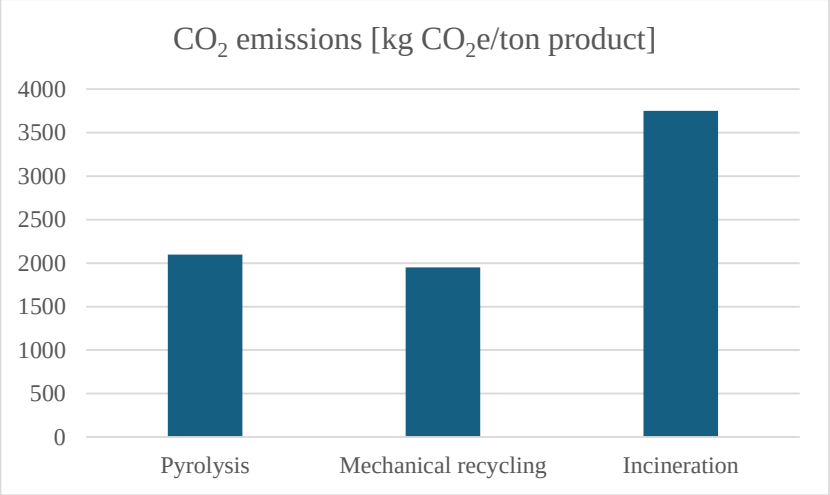

Figure 2.13. Basic figure of CO_2 emissions of end-of-life scenarios for polyolefins in the study of Lange et al. (Lange, 2021).

CO_2 savings of other plastic types such as PET, PA and ABS for mechanical and chemical recycling and, savings of PE for pyrolysis has been also demonstrated in the study (2021), when these results of end-of-life processes were compared with incineration process. Throughout the reviewed LCA studies that accounts different end-of-life scenarios or different plastics in the article, the article (2021) was also found out that carbon intensity of plastics has been observed 4-5 $t_{CO2}/t_{plastic}$. This number of CO_2 emissions has been associated with production stage by nearly 50% and incineration stage as an end-of-life option by 50%, too. It was also indicated that incineration process should be performed with modern gas filtering and clearing technologies, and emitted not harmful gases such as polyaromatic hydrocarbons, nitric oxide (NO_x), sulfur oxide (SO_x) or dioxins to destroy the waste responsibly while generating electricity. Designing of recyclable products and following design guidelines were also associated with helping mechanical recycling processes which is mostly limited to downcycling and led to production of resins with moderate recyclate content. Sorting and product design were also pointed out as practices that can favor larger recycling fractions in the article (2021).

In the article of Lange (2021), it was also revealed recycling types and their effectiveness while performing different waste streams. First, mechanical recycling is expressed with plastic recycling by focusing three packaging polymers of PE, PP and PET, obtaining a monostream fraction has been a crucial factor in it. Process of mechanical recycling has turned wastes into granulates and then, had an ability to mix recycled waste with virgin polymer of same type. For gasification, contaminated waste stream can be performed in contrast to mechanical recycling, and it has also had a potential to provide syngas as a hydrocarbon fuel. Nevertheless, the technology of gasification

has been expensive and should be performed at a large scale by regarding economical aspect. moreover, this technique has released syngas that is known as a low-value product requiring further steps to get other hydrocarbons. For pyrolysis, it has been required sorted plastic waste, but pyrolysis is known for its cheaper practice when it is considered gasification. Depolymerization or solvolysis can also be a technique to handle impurities, but it has become expensive and complex when it has required to accomplish the monomers free from unwanted low-weighted components such as functional additives (dye, antioxidant) or degraded monomers. Moreover, pyrolysis has become a more meaningful alternative when depolymerization is considered, since it has required complex pyrolysis conditions and mainly led to a mixture of hydrocarbons. Especially for polyolefins, melt-pyrolysis technique, which is feeding the plastic and melting it in an extruder with 450-500 ^{o}C to provide pyrolysis oil, is able to achieve a main product of gaseous stream that includes high amount of olefin. So, this process has also become a chemical recycling process by providing monomers of PO plastic waste. However, for other types of polymers such as PET or PVC, pyrolysis has indicated as unsuitable for application. In general, chemical recycling has provided a reasonable option where mechanical recycling is not able to perform the waste streams. It has been able to perform contaminated, mixed streams and to deliver higher-quality products, but it has required to perform in larger scale. For PET and mixed PO, larger scale has been met. For the other plastic types, it has been observed challenges to obtain large scale while chemical recycling is wanted to perform. To recover these other types of plastics which are not able to perform in chemical recycling, landfill included carbon sequestration and avoided leachate has been suggested in the article. For the other cases, as a last option, practice of energy recovery that does not have to require separation of waste streams has been expressed according to article (Lange, 2021).

In another study of Das et al. (2022), it was handled life cycle assessment through end-of-life of pyrolysis for non-recyclable plastics, and pyrolysis has been a focus as an outstanding chemical recycling method (Das et al., 2022). In the article, waste plastics were demonstrated by being able to be pyrolyzed to get naphtha. However, while upgrading plastic wastes to naphtha, some increase on the energy consumption has seemed due to additional steps of naphtha production. The steps of polymer production has been also identified as a cause of increment on the water consumption and GHG emissions. Das et al. (2022) has investigated whether the pyrolysis of non-recyclable waste plastics to virgin plastic (naphtha) was more circular option or upgrading the wastes to fuel was more circular. The study has determined two different functional units of 1 MJ of naphtha fuel and 1 kg of low-density polyethylene (LDPE). Two different pathways, which both include pyrolysis to obtain naphtha from plastic waste, have been established. One of the pathways was plastic waste to main product of naphtha that is utilized as fuel. The other pathway in the article was plastic waste to

ethylene, after providing naphtha from pyrolysis. The ethylene obtained was used to produce polymer of LDPE. Baseline scenarios for non-recycled plastics were selected according to the ratios of conventional waste practices in Europe and U.S. For U.S., 20% incineration and 80% landfill practices were applied for non-recycled plastics (NRP). For EU, as average ratios, 63% incineration and 37% landfill practices were handled. 33% and 8% of plastic waste were sent to recycling for EU and US, respectively. Different electricity grids were also used for US (33% renewable share) and EU (48% renewable share).

Thus, the results of the study of Das et al. (2022) has demonstrated that results of life cycle GHG emissions were 12% lower for naphtha from pyrolysis of NRP, when it was considered the conventional route of naphtha production from crude oil in US. The result of ethylene and LDPE polymer production from NRP via pyrolysis case was also found 18% lower than baseline US – LDPE production scenario which consists of conventional production of LDPE. For EU, GHG emissions were also reached more reduction in LDPE production scenario via pyrolysis of NRP. For plastic-to-plastic scenario (LDPE production) in EU, the result was lower 37% when conventional LDPE production from fossil resources was considered. For plastic-to-fuel scenario in EU, 7% reduction was reached when conventional production of naphtha from fossil resources was considered. It was also revealed that fossil resources consumption were reduced in scenarios of LDPE and naphtha production from waste plastics. It has been much lower in plastic-to-fuel scenario (99%), than plastic-to-plastic (56%). So, these points can be mainly concluded that naphtha and LDPE production from non-recyclable plastics causes less GHG emission for EU and U.S., when it was considered fuel production from pyrolysis (plastic to fuel, P2F). By contrast, for P2F case amounts of waste generation, water, and fossil resource consumption were indicated lower than pyrolysis to production of plastic (plastic to plastic, P2P) case, too. The study has also indicated that, even though GHG emissions were lower in P2P case in EU and US regions, P2F scenario can also be evaluated as an important option that helps reasonable consumption of water and fossil resources for the regions of water and resources-scarcity. Furthermore, in the study, it was explained that other recycling technologies rather than pyrolysis were able to consume less energy and water, also could lead less GHG emissions for P2P scenario (Das et al., 2022).

A different study by Bora et al. (2020) was also studied on plastic recycling methods through their environmental performances (Bora et al., 2020). Methods of chemical recycling technologies as gasification and fast pyrolysis were compared with conventional waste management methods for polypropylene (PP) waste, as a polymer type of polyolefin group, to obtain mitigation of climate change and circular economy requirements. Conventional methods defined in the study have been

mechanical recycling, landfilling and incineration. Chemical recycling technology of gasification in the study was defined as a thermochemical technology that performs partial oxidation of wastes at nearly 1200 ^{o}C. It is able to obtain syngas that is required to be cleaned or upgraded considering its quality. The fuel of syngas can also be sold in the market when its quality is high. Solid char remained after the process has been sent to landfill, not used as a soil amendment. The chemical recycling method of fast pyrolysis was explained as turning waste feedstock into products of lighter gases or heavier bio-oil in an area without oxygen. The process is performed in 300 – 600 ^{o}C which is a temperature range lower than process of gasification. Catalyst is also required to provide fully conversion of waste feedstock. For PP waste in the study was associated with involving contaminants and different utilization areas. This condition of PP waste has been able to make its mechanical recycling harder, and then these wastes have sent to landfill or incineration. These last two conventional methods were correlated with environmental problems by ending up as disposal, and the material has not been able to recover in circular economy. In order to assess environmental benefits and potential of climate change, the impact categories were selected according to LCIA methods of IPCC 2013 (single indicator of GWP), ReCiPe and ILCD 2.0 in midpoint indicators with different units. IPCC 2013 was involved in the study to prevent the confusion among multiple impact categories, with its single environmental indicator. Methods of ReCiPe and ILCD 2.0 were examined since these two had different impact categories (18 and 19 impact categories, respectively) and characterization factors (units). The study was also determined the functional unit as 1 ton of PP waste treated, since the calculations have become easier with this unit.

Through the life cycle assessment evaluation, two methods of fast pyrolysis and gasification have been noted with efficient overall environmental performances, regarding conventional disposal methods of landfilling and incineration. For the most of 18 impact categories in ReCiPe methodology, as it can be seen on Table 2.2., mechanical recycling among these conventional and technological applications has obtained the results with lower/lowest environmental impact scores consistently, according to the study of Bora et al. (2020). The results can see on the example figure of Figure 2.14, which was prepared according to the figure on the study (2020). For normalized scores of GWP-100, mechanical recycling was scored nearly 70%; while fast pyrolysis, gasification, landfill and incineration were scored nearly 75%, 95%, 115% and 77%, respectively. For fossil depletion category, normalized score was lowest for landfill as it was expected; while the environmental impact score was highest for gasification, and then second high score was for fast pyrolysis. For the normalized results of ozone depletion (%110 for fast pyrolysis, %100 for gasification) and photochemical ozone formation (85%, 100%) environmental impact categories, fast pyrolysis and gasification have had higher environmental normalization scores than mechanical

recycling (10% and 30%), too. Another environmental impact category of terrestrial acidification has had the normalized scores of 85%, 100% 10%, 30% and 10% for fast pyrolysis, gasification, landfill, incineration and mechanical recycling, respectively. Contribution of electricity in these high impact category results of fast pyrolysis was also highlighted in the study via figures of contribution analysis diagram of ReCiPe. Mechanical recycling practice has indicated as a reasonable alternative for end-of-life of PP waste, when these results were considered. On the other hand, it was noted in the study of Bora et al. that the model of mechanical recycling utilized in the study was highly idealistic, derived from HDPE recycling process. Thus, it can be concluded that, chemical recycling technologies have been seemed having lower impacts rather than conventional methods, through ReCiPe method. Moreover, for the environment impact category of global warming potential, chemical recycling technologies have been associated with CO_2 emissions up to 807 kg as CO_2-eq/ton polypropylene for gasification, 763.12 kg CO_2-eq/ton PP for mechanical recycling (idealistic) and 619.09 kg CO_2-eq/ton PP for fast pyrolysis which had still better performance values than conventional disposal practices of incineration and landfill with more GHG emission amounts of 876 and 1155 kg CO_2-eq/ton polypropylene. As a result, the study of Bora et al. was concluded chemical recycling technologies of fast pyrolysis and gasification of PP waste have been able to contribute environmental benefits and alleviate climate change (Bora et al., 2020).

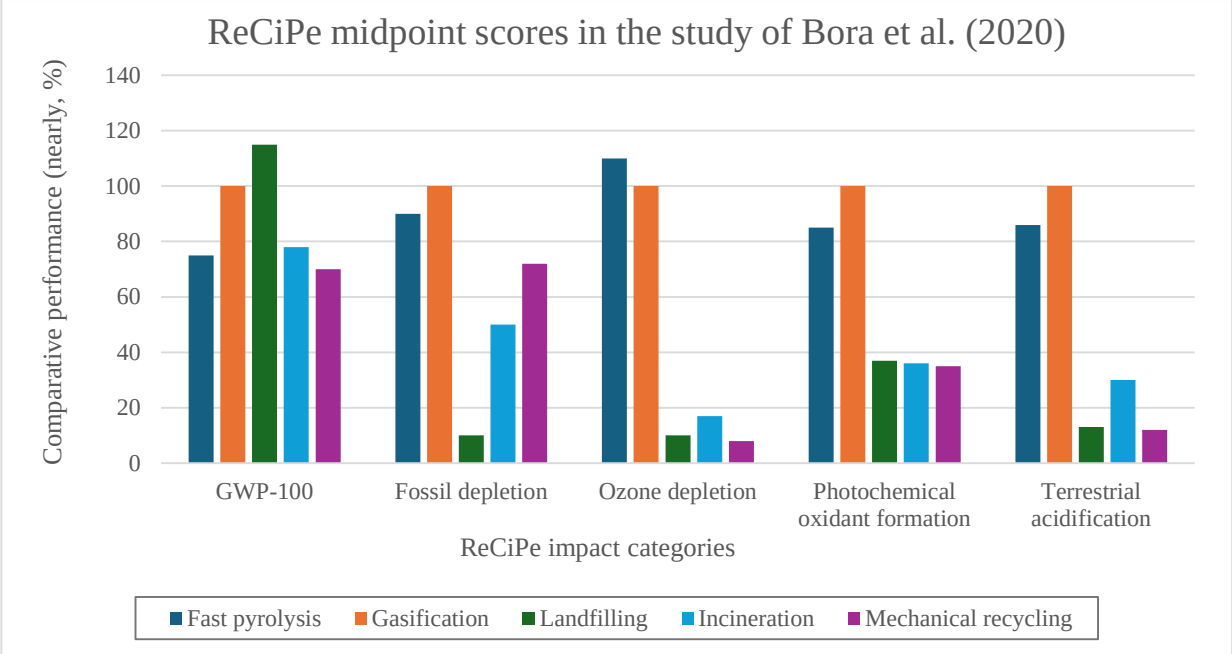

Figure 2.14. Related ReCiPe midpoint scores revealed in the study of Bora et al. (Bora et al., 2020).

Table 2.2. Midpoint indicators and units used for ReCiPe method in the study of Bora et al. (Bora et al., 2020)

.Sr. No.	Midpoint indicator	Impact score unit
1	agricultural land occupation	m^2a
2	climate change	kg CO_2 -eq
3	fossil depletion	kg oil-eq
4	freshwater ecotoxicity	kg 1,4-DC-eq
5	freshwater eutrophication	kg P-Eq
6	human toxicity	kg 1,4-DC-eq
7	ionizing radiation	kg U^{235}-eq
8	marine ecotoxicity	kg 1,4-DB-eq
9	marine eutrophication	kg N-eq
10	metal depletion	kg Fe-eq
11	natural land transformation	m2
12	ozone depletion	kg CFC-11-eq
13	particulate matter formation	kg PM^{10}-eq
14	photochemical oxidant formation	kg NMVOC-eq
15	terrestrial acidification	kg SO_2-eq
16	terrestrial ecotoxicity	kg 1,4-DC-eq
17	urban land occupation	m^2a
18	water depletion	m^3 water-eq

2.4. Electricity Calculations

In a LCA study, electricity grid mix calculations can be prepared for the country which will be studied, if it has been necessary and there has not been a proper dataset present in the software. Electricity grid mix used in each step of a LCA study for plastic, can be required an adapted dataset to get a specific assessment for the country studied. TEİAŞ electrical data which includes sources of energy and energy sources contribution can be utilized in a LCA study (ustun odabasi & Büyükgüngör, 2022). So, the current situation and future projections of Turkey were investigated to obtain clear result in LCA studies of Turkey. The current situation of electricity power generation share in Turkey has obtained from TEİAŞ dataset, as it can be seen on the Figure 2.15 below. In the TEİAŞ electricity generation dataset prepared via 2022 data, it has indicated the renewable energy share on 42.39% and, it has not been high enough to reach net zero emission targets (TEİAŞ, 2022). For European countries of Italy and Spain, the renewable energy shares in current electricity power generation had already been integrated into electricity grid mix and given in LCA software of GaBi 9.1.2 (GaBi 9.1.2 software, 2020). In Spain, the studied electricity grid mix dataset was shown on Figure 2.16, with 47.51% share of renewable energy resources in total. Then in Italy, electricity grid

mix dataset, which is examined in this study, was shown on Figure 2.17 with 35.44% share of renewable energy resources in total.

An improved future renewable energy share on electricity utilized in LCA software have also been studied by Moretti et al. (2021), by considering each LCA stages in a cradle-to-grave study of single-use plastics of PP, PET and a bio-based plastic type of polylactide (PLA). Processes in LCA stages which consumes electricity have been able to be assessed with this new-renewable energy share in electricity usage, and a comparison between environmental impacts obtained have been studied (Moretti et al., 2021). Impacts of utilization of increased renewable energies in electricity production was also studied in a LCA of plastic pellets by Saleem et al. (2023), too. An implementation of solar PV renewable energy share in electricity data has been used rather than natural gas in LCA of recycled plastic pellets, and the renewable share on electricity has led to the reduction in most of environmental impact category results (Saleem et al., 2023). When it comes to future projections, Turkey National Energy Plan prepared by Republic of Türkiye Ministry of Energy and Natural Resources has been examined as a guide to indicate future renewable energy usage projections and renewable energy sources while generating electricity. To achieve the target of net zero emission, developments in the future electricity scenarios have been expected by depending more on renewable resources (Republic of Türkiye Ministry of Energy and Natural Resources, 2022). Below figures of Figure 2.18, 2.19 and 2.20 on the next pages, the future electricity scenario studied in the Turkey National Energy Plan has been shown.

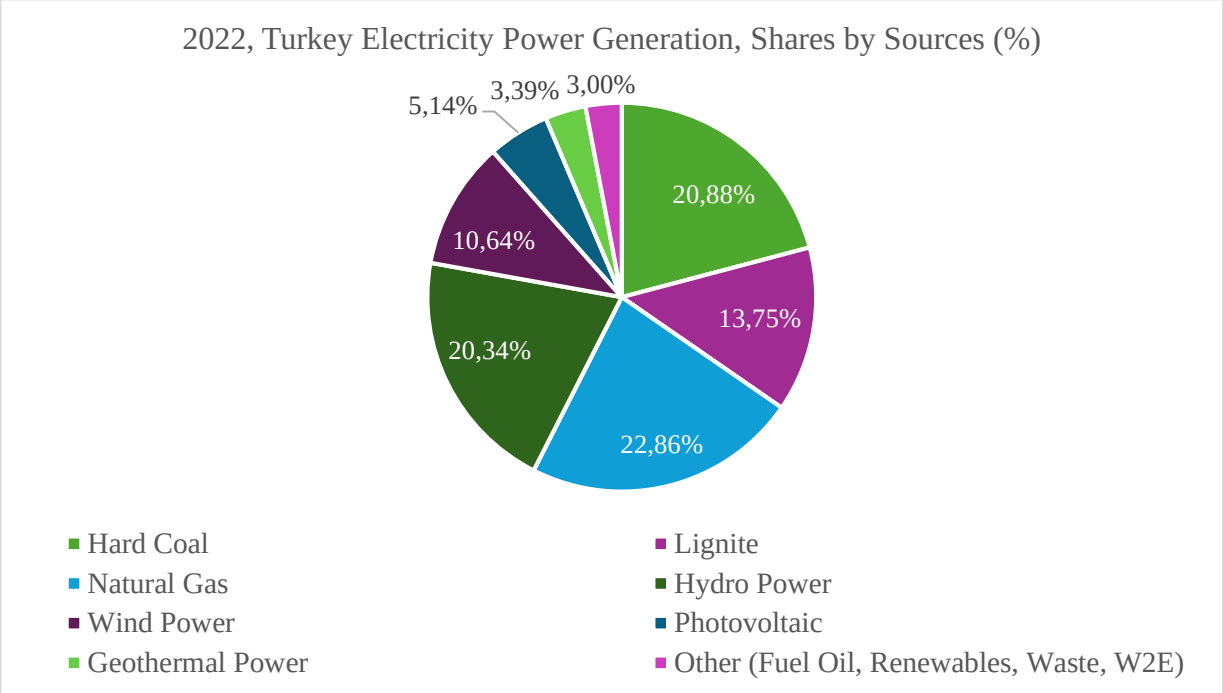

Figure 2.15. 2022, Turkey Electricity Power Generation Shares by Sources (%) (TEİAŞ, 2022).

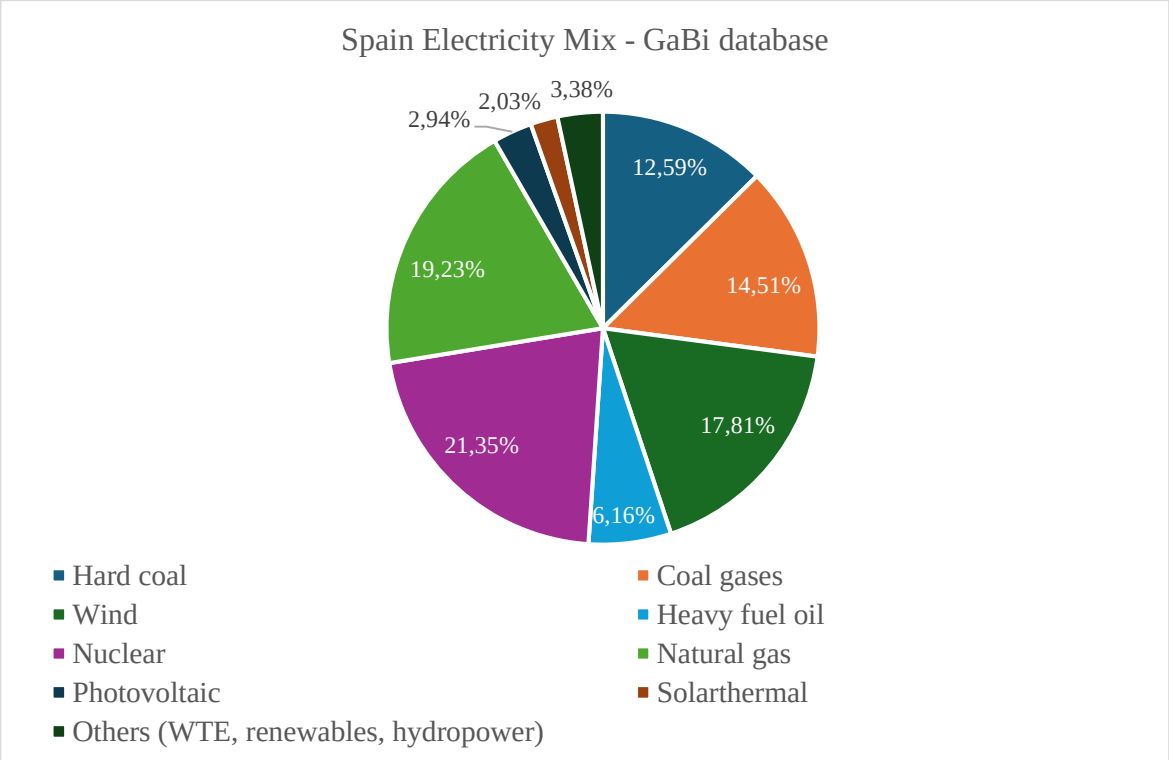

Figure 2.16. Electricity Grid Mix in GaBi – for Spain (%) (GaBi database 9.1.2, 2020).

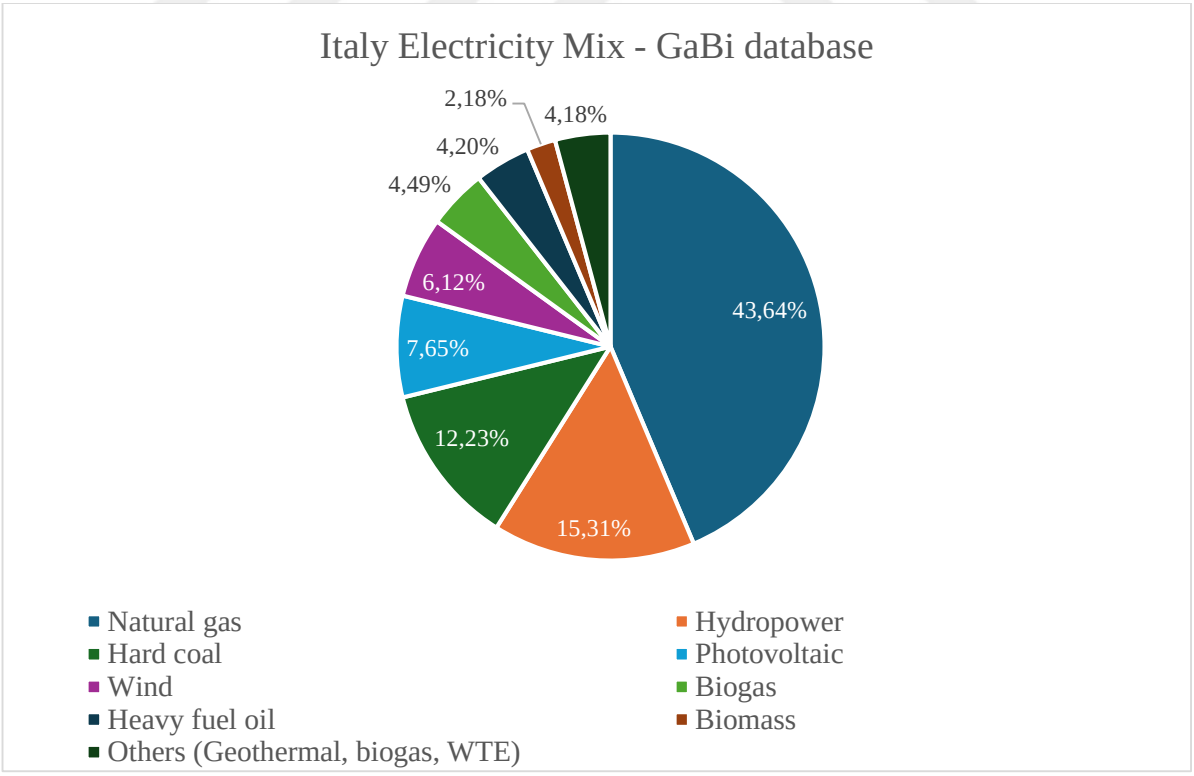

Figure 2.17. Electricity Grid Mix in GaBi – for Italy (%) (GaBi software 9.1.2, 2020).

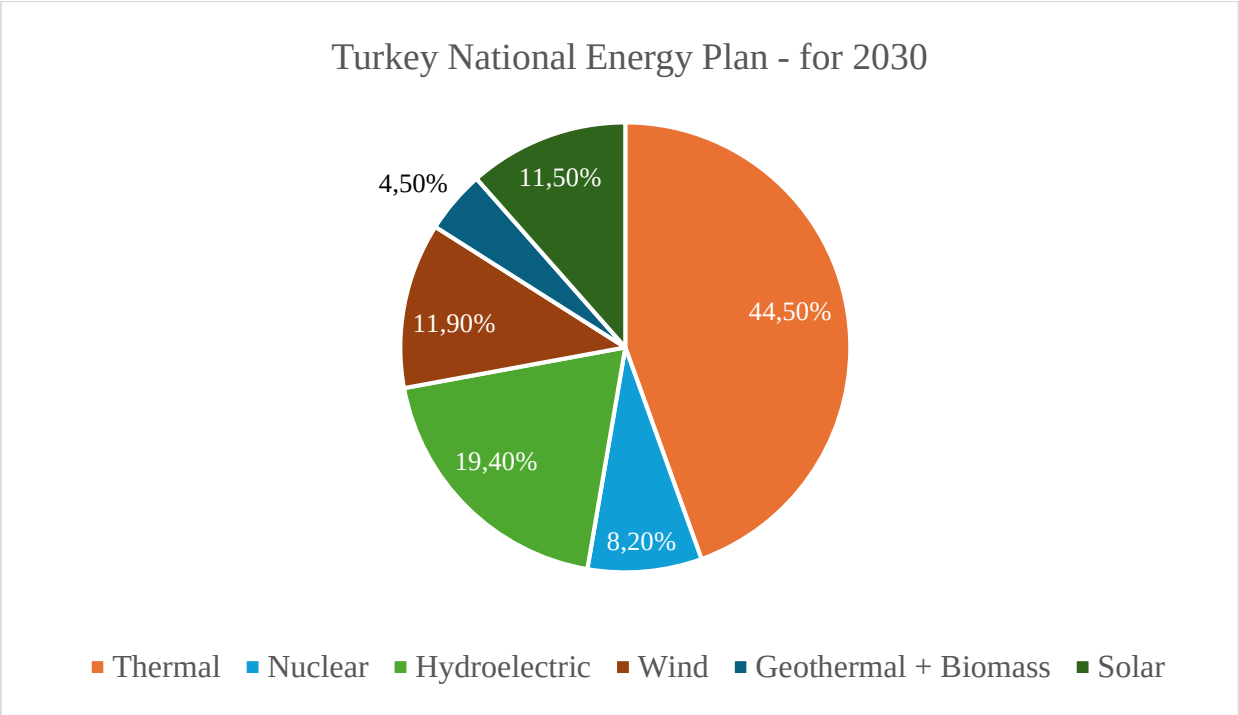

Figure 2.18. Distribution of Electricity Generation by Sources for 2030 (%) (Republic of Türkiye Ministry of Energy and Natural Resources, 2022).

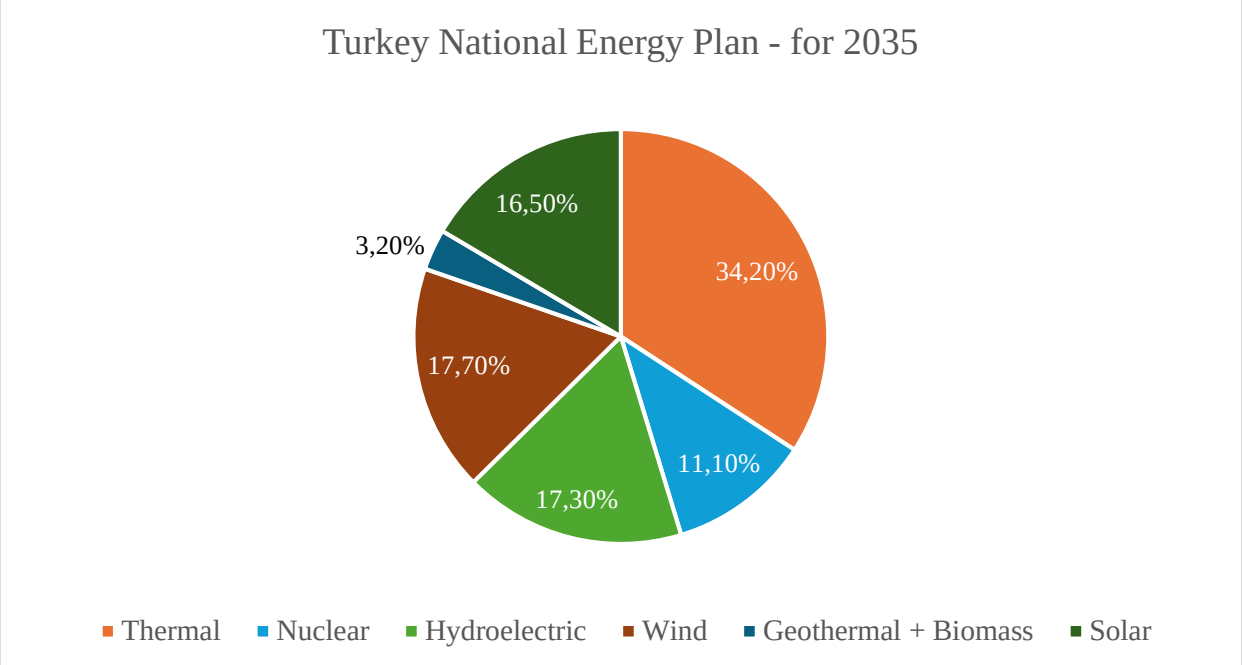

Figure 2.19. Distribution of Electricity Generation by Sources for 2035 (%) (Republic of Türkiye Ministry of Energy and Natural Resources, 2022).

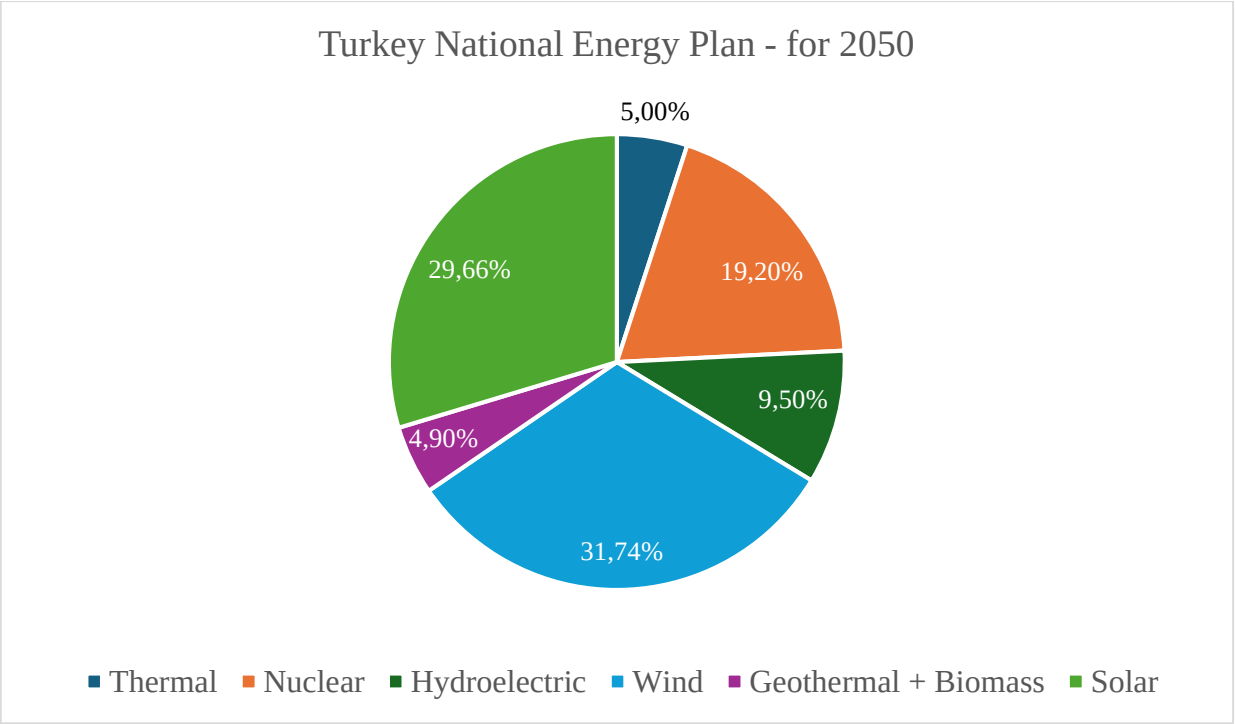

Figure 2.20. Distribution of Electricity Generation by Sources for 2050, adapted from information (%) (Republic of Türkiye Ministry of Energy and Natural Resources, 2022).

3. MATERIALS AND METHODS

Life cycle assessment methodology is applied to evaluate the potential environmental impacts, inputs and outputs of selected products for defined scenarios with a thorough understanding of principles and framework in ISO 14040:2006 and qualifications and guidelines in ISO 14044:2006, have been involved. The framework of LCA which has been integrated in this study follows four phases: goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA) and interpretation (Auras & Selke, 2023; Gómez & Escobar, 2022).

3.1. Goal and Scope Definition

The aim of this study is to evaluate and compare effects of different end-of-life scenarios by performing life cycle analysis of three most used consumer goods plastic packaging materials of polyethylene-terephthalate (PET), polyolefins (PO), and polystyrene (PS) for different environmental impact categories. Since life stages of these three packaging materials have very complex processes from the beginning of petroleum refineries and crude oil resource to their disposal as plastic waste and, their detrimental impact to environment is considerable, it is important to handle LCA studies.

Selected environmental impact categories for this study are global warming potential, ozone layer depletion, photochemical ozone formation, acidification, and resource depletion. By performing life cycle assessment with different end-of-life scenarios; three selected plastic waste types, were assessed by considering EU Green Deal 2030 and 2035 future plastic waste management targets for three Mediterranean countries of Turkey, Italy and Spain. For Turkey, it was evaluated 2050 scenario because of target related to 2053 Net Zero Emission and for two European countries, 2050 scenario, which can potentially present a roadmap for Net Zero CO_2 emission, was evaluated. Process data of packaging materials was accessed via GaBi 9.2.1 software.

The end-of-life scenarios with different recycling, energy recovery/incineration and landfilling rates were studied with different electricity grid mix data, obtained via GaBi 9.2.1 software for the European countries of Italy and Spain (Figure 2.16 and 2.17). For future European scenarios, the same Italy and Spain electricity grid mix data were used for comparison. There was not an

appropriate data set related with Turkish electricity grid mix on GaBi software. So, the related data was taken from TEİAŞ website, Electricity Power Production and Consumption – Losses" section and "Year of 2022, Turkey Distribution of Electricity Generation by Sources", and adapted to GaBi software electricity grid mix (Figure 2.15, 3.2) (TEİAŞ, 2022). For future Turkish scenarios of 2030 and 2050, details of "Distribution of Electricity Generation by Sources" electricity scenario in Türkiye National Energy Plan was utilized and adapted to GaBi software (Figure 2.18, 2.19, 2.20 and Figure 3.4, 3.5). For the year of 2050, there was not a direct table of electricity scenario, so the 2035 scenario (Figure 2.19) and the information on the Turkey National Energy Plan were adapted by shares to obtain a table. In the 2050 scenario, renewable energy sources for electricity generation have been specified as 61.4% for wind and solar energy in total. It is also indicated that thermal energy sources of natural gas-fired power plants and coal-fired power plants will be decreased until 2053, gradually. So, the ratio of thermal energy sources for the year of 2050 was decreased in the distribution of electricity generation (Figure 2.20). It is also mentioned about hydroelectric power plants share on the Turkey National Energy Plan, which will decrease its share related to its reduced maximum capacity in long term, then the ratio was kept under 10% (Figure 2.20) (Republic of Türkiye Ministry of Energy and Natural Resources, 2022).

The ratios of recycling, energy recovery/incineration and landfill in the different end-of-life scenarios were chosen with respect to plastic packaging waste policy targets determined by European Commission. It is indicated as 55% for plastic packaging waste for the year of 2030. For 2022, recycling rates in Italy and Spain had not met the target rate of 55%, with the rates of 52% for Italy and 49% for Spain. Landfilling and energy recovery options for plastic packaging waste end-of-life options were determined according to Plastics Europe data, too (Plastics Europe, 2024). So, current situation's scenario, 2030 and 2050 recycling scenarios were assessed for Italy and Spain with gradually increased share of recycling for 2050. The remaining share was distributed to incineration/energy recovery for European scenarios.

For the scenarios of Turkey, the scenario of current situation was indicated by assessing landfilling and recycling options. The packaging plastic waste recycling target of 55% was determined at Packaging Waste Control Directive (Republic of Türkiye Ministry of Environment, Urbanization and Climate Change, 2021). According to ÇEVKO Foundation data, the current recycling rate has already met the target of 55% for plastic packaging waste (ÇEVKO Foundation, 2024). TUIK waste statistics data was also considered while adding the landfill share in the scenario of current situation (TUIK, 2022). So, the ratios of current scenario, 2030 and 2050 end-of-life

scenarios for Turkey were defined by distributing the shares of energy recovery/incineration, landfilling and recycling by considering recycling target rate (Table 3.1).

There are also packaging reduction targets indicated by European Commission, as 5% reduction by 2030, 10% by 2035 and 15% by 2040 (European Parliament, 2023). For the year of 2050, a reduction of 25% is also implemented to the scenarios of Italy and Spain to the 1000 kg of each plastic material of PET, PO and PS.

Table 3.1. Plastic Packaging Materials (PET, PO [PE & PP] and PS) Scenarios for Turkey, Italy and Spain.

Scenarios of Plastic Packaging Materials for Turkey, Italy (IT) & Spain (ES)	**Recycling Share in Scenario (%)**	**Incineration / Recovery Share in Scenario (%)**	**Landfill Share in Scenario (%)**	**Implemented Future Improvement: Electricity Grid Mix Used or Reduction of Packaging Waste (%)**
Current situation for Turkey	55	-	45	Current situation (No improvement; TEİAŞ, 2022; **41.51% renewable** energy in electricity production)
Current situation for Italy & Spain	ES: 50	ES: 16	ES: 34	Current situation (No improvement; not implemented reduction of packaging waste; **47.51%** renewable in ES electricity production & **39.93%** renewable share in IT electricity production)
	IT: 45	IT: 49	IT: 6	
2030 scenario for Turkey	55	45	-	Electricity Grid Mix Used: 2030 – NEP Electricity (**55.5% renewable** energy share in electricity production)
2030 scenario for Italy & Spain	55	45	-	Reduction of Packaging Waste: 5%
2050 scenario for Turkey	80	20	-	Electricity Grid Mix Used: 2050 – NEP Electricity (**95% renewable** energy share in electricity production)
2050 for Italy & Spain	80	20	-	Reduction of Packaging Waste: 25%

3.1.1. Functional Unit, System Boundaries

Functional unit is a reference unit that implies “quantified performance of a product system” (ISO 14040/44, 2006, 2018). Since LCA is a relative approach, functional unit forms a structure for LCA, and indicates what is being examined. Analyses, all input and output values handled in the study become relative to the functional unit (Finkbeiner et al., 2006). In this study, the functional unit was chosen as 1000 kg plastic packaging compound for all three packaging materials of PET, PO, and PS, since the scenarios in the study can produce 1000 kg of each packaging material.

A scientific boundary and scope definition have a significant impact to obtain accurate results in a LCA study (Li et al., 2013). Crude oil production from its resource, petroleum refining coproduct formation from crude oil at consumer country, resin/granulate production of each polymer of PET, PS and PO, plastic compound moulding step, end-of-life options of recycling and energy recovery/incineration and electricity consumptions were included in the system boundaries. All transportation and distribution steps of packaging material for production, consumption and end-of-life; packaging of consumer goods in related consumer good companies and consumption of packaging material were excluded from system boundaries in the study, as it can be seen on the Figure 3.1.

There have been four different production scenarios for three types of packaging materials. Two different polymer sub-types of polyolefins, polyethylene (PE) and polypropylene (PP), polystyrene (PS) and polyethylene-terephthalate (PET) were included in the scenarios. The production, recycling and incineration steps of three packaging materials have followed same previous production processes in the scenarios for all three countries of Turkey, Italy and Spain (Figure 3.2). It was used different electricity grid mix data in these scenarios of the packaging materials for different countries: TEİAŞ – 2022 (Figure 2.15 and 3.3), future Türkiye National Energy Plan 2030, 2035 and 2050 (Figure 2.18, 2.19, 2.20 and Figure 3.4, 3.5) for Turkey, ES – 2016 (Figure 2.16) for Spain, IT – 2016 (Figure 2.17) for Italy.

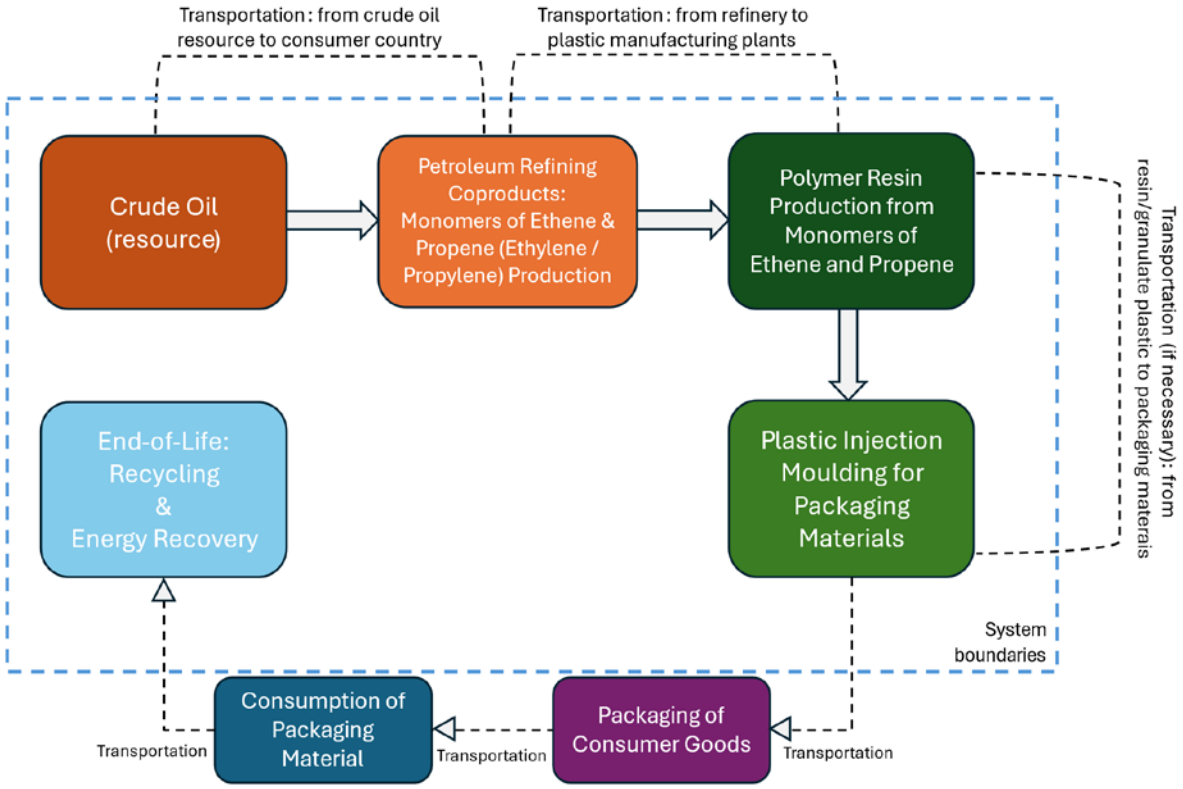

Figure 3.1. System Boundaries.

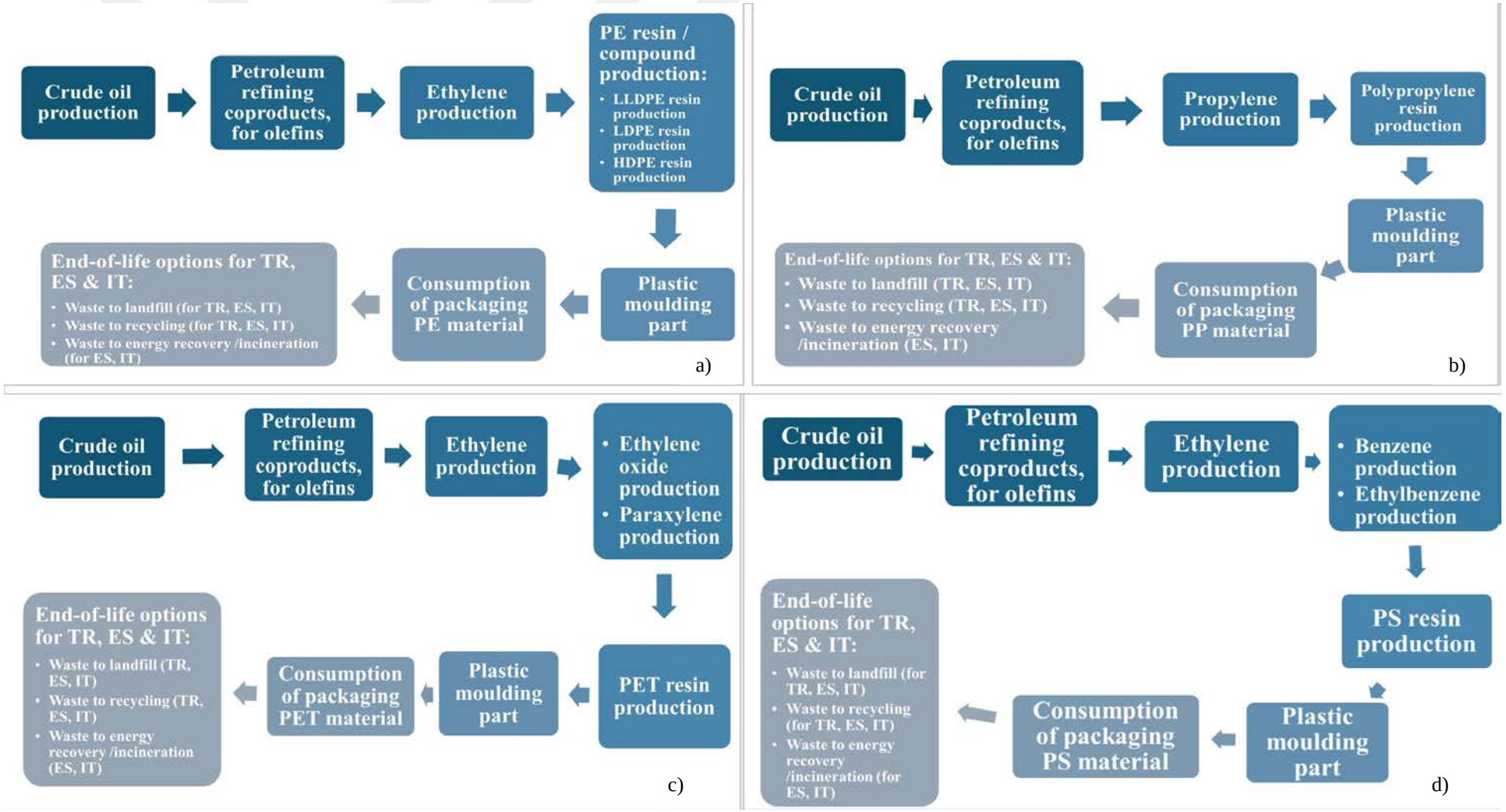

Figure 3.2. Current situation scenarios prepared for life cycles of packaging materials in GaBi 9.1.2 software: a) PE, b) PP, c) PET, d) PS, from crude oil extraction to different end-of-life options for Turkey (TR), Spain (ES) and Italy (IT).

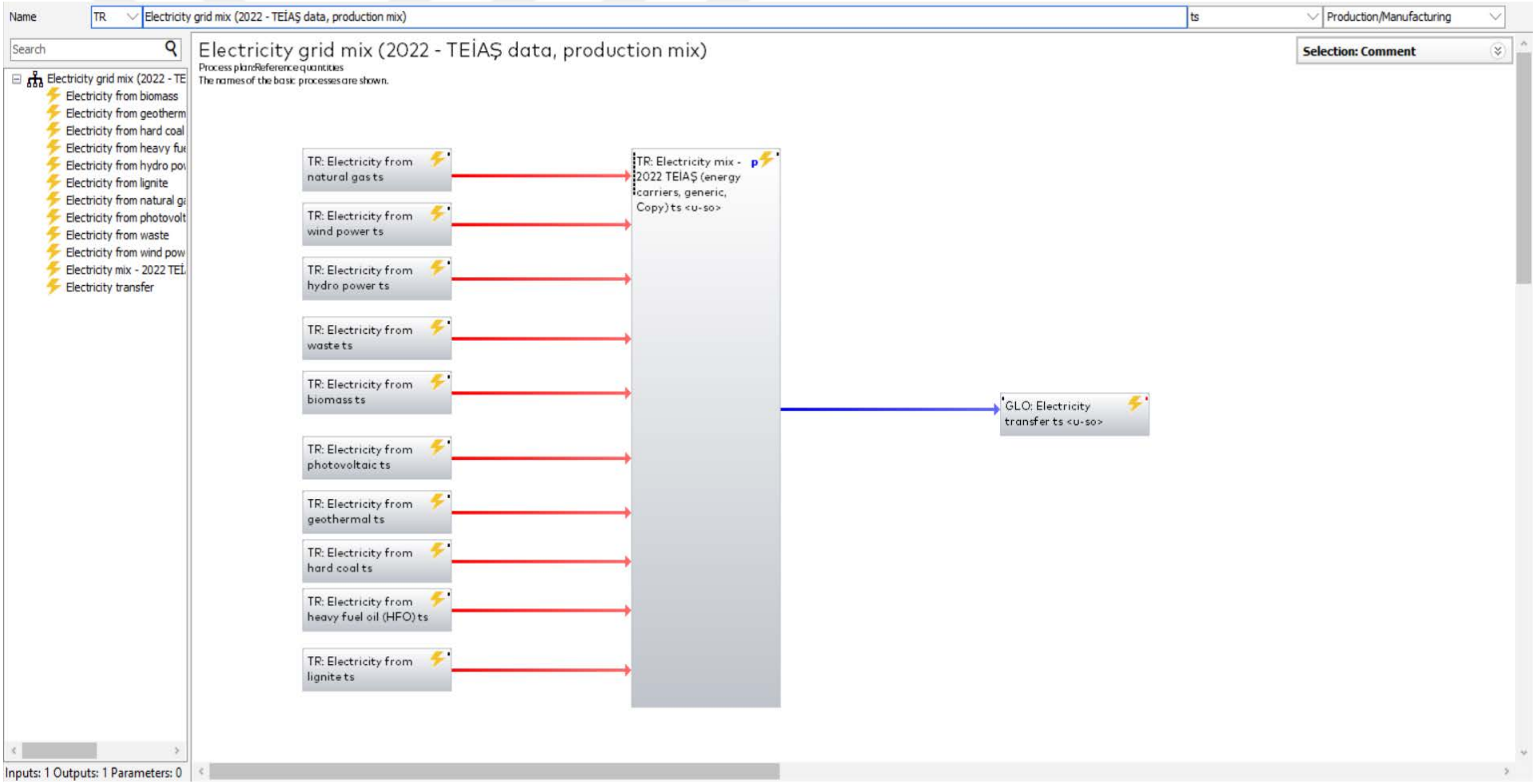

Figure 3.3. TEİAŞ – 2022 electricity grid mix, adapted to GaBi software.

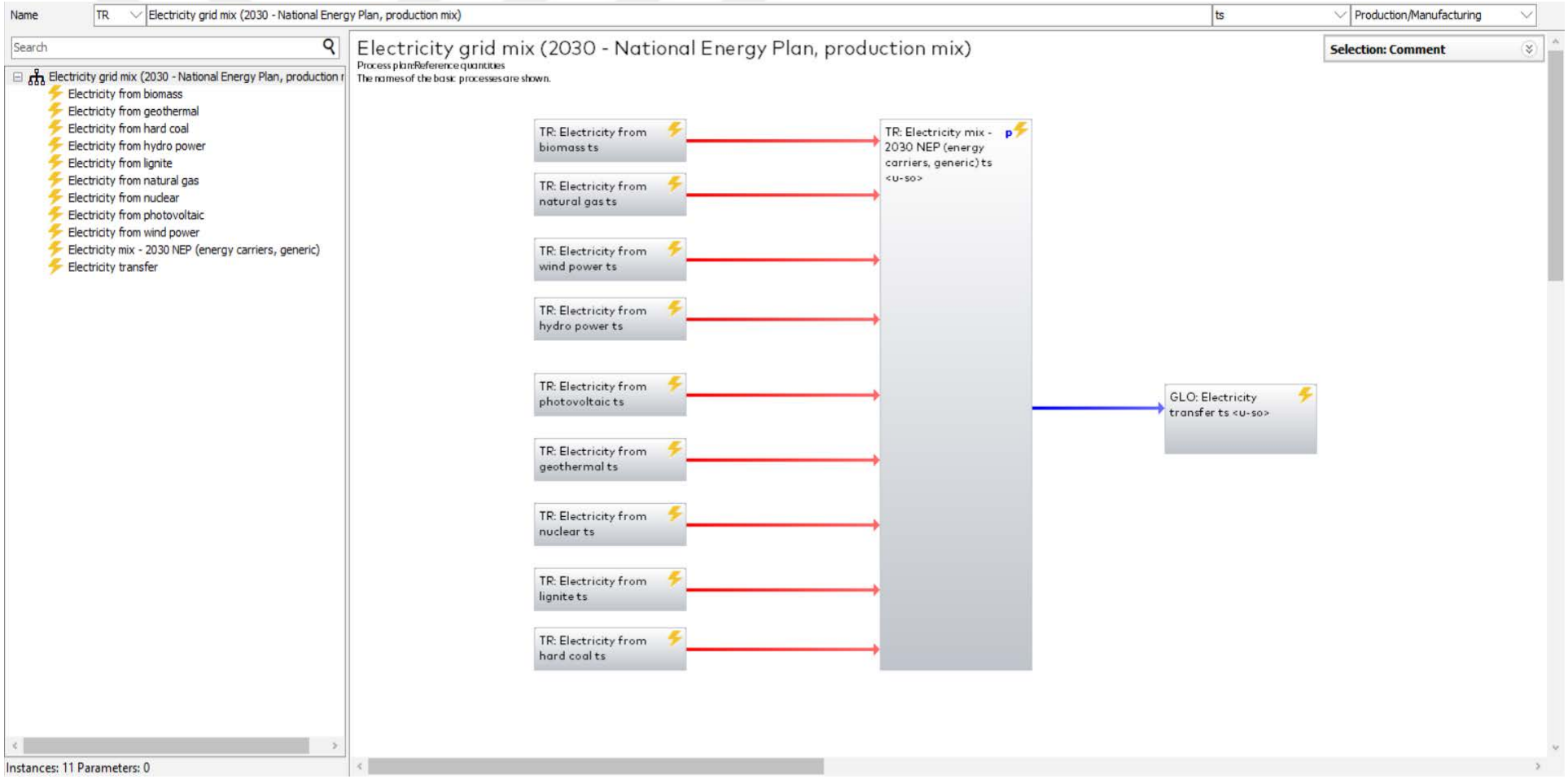

Figure 3.4. Turkey 2030, National Energy Plan electricity grid mix, adapted to GaBi software.

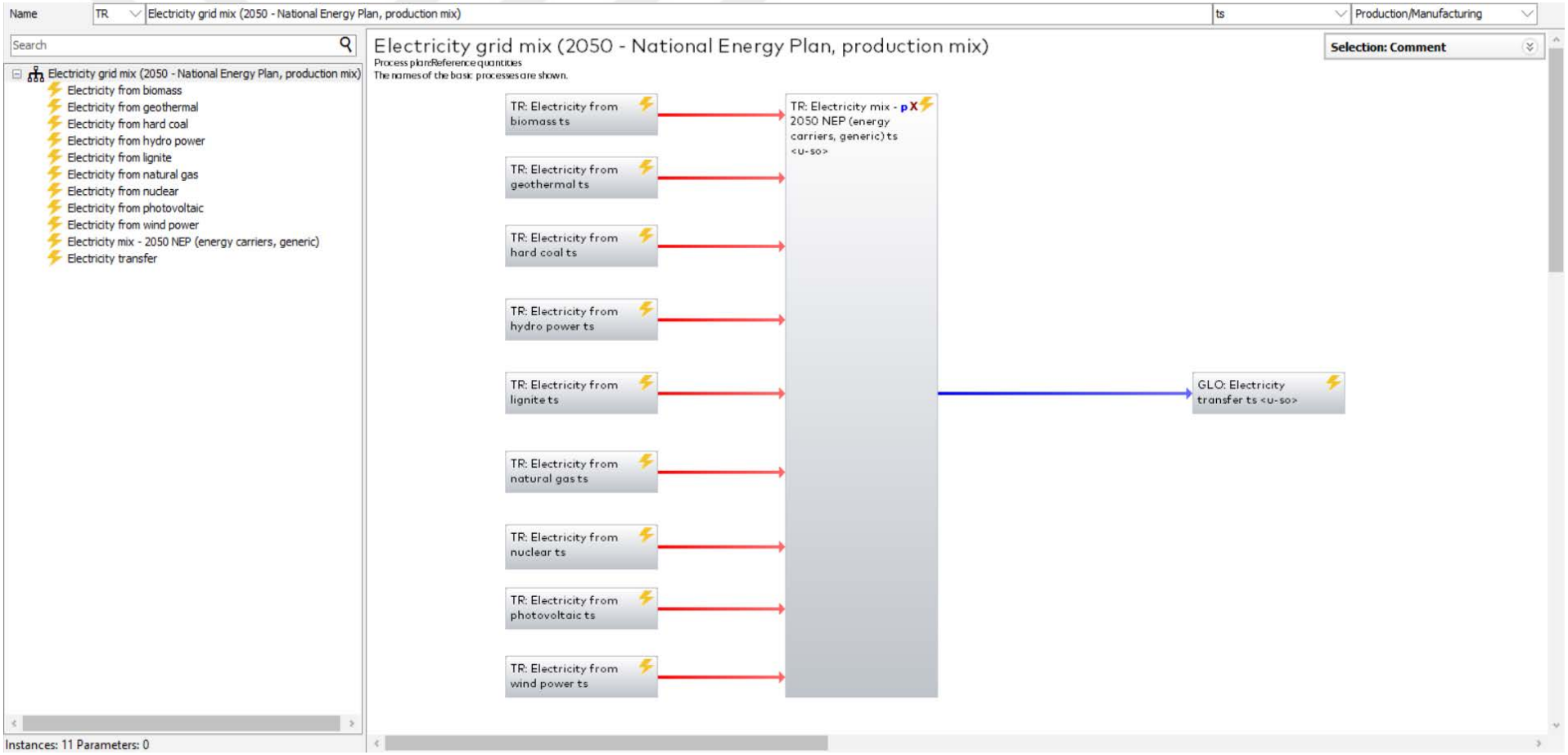

Figure 3.5. Turkey 2050, National Energy Plan electricity grid mix, adapted to GaBi software.

3.2. Life Cycle Inventory Analysis and Key Assumptions

Life cycle inventory analysis is defined as an analysis that helps the estimation of energy requirement and raw material, emissions, wastes and pollutants. Then, the result of an inventory analysis leads an estimation raw material, energy consumption and produced pollutant amount during the process (Ramanathan et al., 2022).

Table 3.2. Required data – amounts of consumption in the scenarios for PO, PS, and PET

	Specific required data for each packaging material (from GaBi 9.1.2 software, Educational Database 2020)	**Mutual required data for all packaging material (from GaBi 9.1.2 software, Educational Database 2020)**
Scenarios for PO (Polyethylene Group) Production for Turkey, Italy and Spain	- Ethylene consumption, - Polyethylene resin - granulate (low density polyethylene, linear low-density polyethylene, high density polyethylene) consumption	- Electricity consumption in all steps, - Crude oil (resource) consumption, - Packaging waste consumption in the processes of recycling and energy recovery / incineration
Scenarios for PO (Polypropylene Group) Production for Turkey, Italy and Spain	- Propylene consumption, - Polypropylene resin - granulate consumption	
Scenarios for PET Production for Turkey, Italy and Spain	- Ethylene consumption, - Ethylene oxide (ethylene glycol) consumption, Paraxylene consumption, - Polyethylene terephthalate resin - granulate consumption	
Scenarios for PS Production for Turkey, Italy and Spain	- Ethylene consumption, - Ethylbenzene consumption, - Benzene consumption, - General purpose polystyrene compound consumption	

Table 3.3. Scenarios for countries, with different electricity grids for Polyolefins (Polyethylene Group).

Life cycle stage	Processes	Input Flows in GaBi 9.2.1 Software	Output Flows in GaBi 9.2.1 Software
Raw Material Extraction	Crude oil at production	Crude oil (resource) in kg Electricity (MJ)	Crude oil (at consumer) in kg
	Crude oil at refinery	Crude oil (at consumer) in kg Electricity (MJ)	Petroleum refining coproduct, for olefins production in kg
Manufacturing	Ethylene production	Petroleum refining coproduct, for olefins production Electricity (MJ)	Ethene (Ethylene) (Organic intermediate products) in kg
	LLDPE, LDPE and HDPE resins production at plant	Ethene (Ethylene) (Organic intermediate products) in kg Electricity (MJ)	LLDPE (Linear low-density polyethylene) in kg LDPE (Low density polyethylene) in kg HDPE (High density polyethylene) in kg
	Plastic injection moulding part	Polyethylene low density compound - granulate (LDPE/PE-LD) in kg Polyethylene linear low-density compound - granulate (HDPE/PE-HD) in kg Polyethylene high density compound - granulate (HDPE/PE-HD) in kg Tap water in kg Electricity (MJ)	Polyethylene packaging material (in kg)
End-of-life	After consumption of packaging material - Alternative end-of-life option - 1: Recycling	Packaging waste (consumer waste) in kg Electricity (MJ)	Recycled postconsumer PE pellet (in kg)
	After consumption of packaging material - Alternative end-of-life option - 2: Energy Recovery / Incineration	Incineration good (consumer waste) in kg	Electricity (MJ) Steam (MJ)
	After consumption of packaging material - Alternative end-of-life option - 3: Landfill	Landfill of plastic waste (consumer waste) in kg	Landfill waste (kg)

Table 3.4. Scenarios for countries, with different electricity grids, for Polyolefins (Polypropylene Group).

Life cycle stage	Processes	Input Flows in GaBi 9.2.1 Software	Output Flows in GaBi 9.2.1 Software
Raw Material Extraction	Crude oil at production	Crude oil (resource) in kg Electricity (MJ)	Crude oil (at consumer) in kg
	Crude oil at refinery	Crude oil (at consumer) in kg Electricity (MJ)	Petroleum refining coproduct, for olefins production in kg
Manufacturing	Propylene production	Petroleum refining coproduct, for olefins production in kg Electricity (MJ)	Propene (Propylene) (Organic intermediate products) in kg
	Polypropylene resin production, at plant	Propene (Propylene) (Organic intermediate products) in kg Electricity (MJ)	Polypropylene compound (PP) in kg
	Plastic injection moulding part	Polypropylene compound (PP) in kg Tap water (in kg) Electricity (MJ)	Packaging material (in kg)
End-of-life	After consumption of packaging material - Alternative end-of-life option - 1: Recycling	Packaging waste (consumer waste) in kg Electricity (MJ)	Recycled postconsumer pellet (in kg)
	After consumption of packaging material - Alternative end-of-life option - 2: Energy Recovery / Incineration	Incineration good (consumer waste) in kg	Electricity (MJ) Steam (MJ)
	After consumption of packaging material - Alternative end-of-life option - 3: Landfill	Landfill of plastic waste (consumer waste) in kg	Landfill waste (kg)

Table 3.5. Scenarios for countries, with different electricity grids, for Polyethylene-terephthalate (PET).

Life cycle stage	Processes	Input Flows in GaBi 9.2.1 Software	Output Flows in GaBi 9.2.1 Software
Raw Material Extraction	Crude oil at production	Crude oil (resource) in kg Electricity (MJ)	Crude oil (at consumer) in kg
	Crude oil at refinery	Crude oil (at consumer) in kg Electricity (MJ)	Petroleum refining coproduct, for olefins production in kg
Manufacturing	Ethylene production	Petroleum refining coproduct, for olefins production Electricity (MJ)	Ethene (Ethylene) (Organic intermediate products) in kg
	Ethylene oxide & P-Xylene production, at plant	Ethene (Ethylene) (Organic intermediate products) in kg Oxygen liquid (in kg) Electricity (MJ)	Ethylene oxide [Organic intermediate products] (in) kg
		Xylene-mix (Dimethylbenzene) [Organic intermediate products] in kg Electricity (MJ)	Xylene (p-xylene; 1,4-dimethyl benzene) [Organic intermediate products] (in kg)
	Polyethylene-terephthalate resin production, at plant: Ethylene oxide + P-Xylene → Polyethylene-terephthalate	Ethylene oxide [Organic intermediate products] in kg Xylene (p-xylene; 1,4-dimethyl benzene) [Organic intermediate products] in kg Electricity (MJ)	Polyethylene terephthalate compound (PET) in kg
	Plastic injection moulding part	Polyethylene terephthalate compound (PET) in kg Tap water (in kg) Electricity (MJ)	Packaging material (in kg)
End-of-life	After consumption of packaging material - Alternative end-of-life option - 1: Recycling	Packaging waste (consumer waste) in kg Electricity (MJ)	Recycled postconsumer pellet (in kg)
	After consumption of packaging material - Alternative end-of-life option - 2: Energy Recovery / Incineration	Incineration good (consumer waste) in kg	Electricity (MJ) Steam (MJ)
	After consumption of packaging material - Alternative end-of-life option - 3: Landfill	Landfill of plastic waste (consumer waste) in kg	Landfill waste (kg)

Table 3.6. Scenarios for countries, with different electricity grids, for Polystyrene (PS).

Life cycle stage	Processes	Input Flows in GaBi 9.2.1 Software	Output Flows in GaBi 9.2.1 Software
Raw Material Extraction	Crude oil at production	Crude oil (resource) in kg Electricity (MJ)	Crude oil (at consumer) in kg
	Crude oil at refinery	Crude oil (at consumer) in kg Electricity (MJ)	Petroleum refining coproduct, for olefins production in kg
Manufacturing	Ethylene production	Petroleum refining coproduct, for olefins production Electricity (MJ)	Ethene (Ethylene) (Organic intermediate products) (in kg)
	Benzene production	Pyrolysis gas (Organic intermediate products) in kg Electricity (MJ)	Benzene (Organic intermediate products) (in kg)
	Ethylbenzene production	Ethene (Ethylene) (Organic intermediate products) in kg Electricity (MJ) Benzene (Organic intermediate products) in kg	Styrene (Organic intermediate products) in kg
	Polystyrene production, at plant	Styrene (Organic intermediate products) in kg Electricity (MJ)	Polystyrene compound (PS) in kg
	Plastic injection moulding part	Polystyrene compound (PS) in kg Tap water in kg Electricity (MJ)	Packaging material in kg
End-of-life	After consumption of packaging material / Waste - Alternative end-of-life option - 1: Recycling	Packaging waste (consumer waste) in kg Electricity (MJ)	Recycled postconsumer pellet (in kg)
	After consumption of packaging material / Waste - Alternative end-of-life option - 2: Energy Recovery / Incineration	Incineration good (consumer waste) in kg	Electricity (MJ) Steam (MJ)
	After consumption of packaging material - Alternative end-of-life option - 3: Landfill	Landfill of plastic waste (consumer waste) in kg	Landfill waste (kg)

Key assumptions in this study were determined by considering data availability. Electricity consumption data which is correlated with each plastic type were assumed to be similar for selected countries. As the electricity consumption data in the literature was not satisfactory for each unit operation of plastic packaging material production, the electricity consumption data in the GaBi 9.1.2 – US Life Cycle Inventory database (USLCI) for each process were utilized in each scenario, except for the processes of energy recovery/incineration, landfill and moulding which have utilized from GaBi 9.1.2 – thinkstep database (ts). It was assumed that each country has the same route of production for each selected plastic packaging material and moreover also was agreed that each plastic material was performed under same recycling process which exists in GaBi 9.1.2 database. Another assumption was related to injection molding process that is performed with same amount of electricity requirement for each packaging material, the process was adapted from unspecific plastic injection molding on GaBi 9.1.2 database. The electricity mix utilized currently in Turkey was assumed TEİAŞ electricity data which includes sources of energy and their contribution, the electricity information on TEİAŞ data was adapted and included to GaBi 9.1.2 electricity grid mix. It was also assumed that scenarios with future implementations on renewable energy shares of electricity production were utilized from Turkey National Energy Plan's electricity scenarios. The electricity mix utilized currently in Italy and Spain were assumed the same electricity grid mix in GaBi database (Finnveden & Potting, 2014).

Petroleum was also assumed as the main feedstock for monomers of the polymers in this study, natural gas is not assumed as a feedstock to obtain monomers. Naphtha production in one of steps of polymer production was also assumed, according to Wiley's book, too. It was indicated in Table 3.3, 3.4, 3.5 and Table 3.6 as "petroleum refining coproduct, for olefins production" (Wiley, 2016). Crude oil is not directly performed under catalytic cracking, so catalytic cracking process was not included in the life cycle of plastics as it can be seen on Table 3.3, 3.4, 3.5 and Table 3.6. Instead of catalytic cracking, naphtha production as petroleum refining coproduct, for olefins production is included in this study as a basic option (Speight, 2011). All polymer types in this study are assumed to be performed under injection molding process, instead of other molding processes of extrusion, blow molding process as it was displayed on Table 3.3, 3.4, 3.5 and Table 3.6 as "plastic injection molding part". As injection molding process is a widespread process for packaging materials, this process and their data presented in GaBi were performed in this study (Wiley, 2016).

4. RESULTS AND DISCUSSION

4.1. Life Cycle Impact Assessment

The purpose of life cycle impact assessment is to evaluate the results that revealed in life cycle inventory analysis and turn the LCI results into the potential environmental impact magnitudes, thus the LCI results are reformed into a clearly understandable quantities (Finnveden & Potting, 2014). Steps of life cycle impact assessment includes classification, to determine the environmental impact categories will be evaluated and to attribute the results of LCI to each environmental impact categories, characterization, to model the emissions quantitatively in the LCI results and resulting in impact scores, normalization and weighting. Normalization and weighting steps are optional according to the ISO. Normalization is the step the characterised impact scores turns into comparable impact scores without reference units. Weighting is the step where a relative importance of environmental impact scores can be obtained (European Commission, 2010).

4.1.1. Classification

As it was mentioned, classification step includes determining environmental impact categories that are going to be studied, then LCIA results of emissions are modelled according to these categories. For this study, impact categories of depletion of abiotic resources, acidification, climate change, ozone layer depletion and photochemical ozone formation were selected. These impact categories were studied in CML2001 - Jan.2016 and ReCiPe 2016 v1.1 LCIA methodologies. In Table 4.1., studied environmental impact categories were indicated with their reference units in each method.

Table 4.1. Selected impact categories.

Depletion of Abiotic Resources	CML2001 - Jan. 2016, Abiotic Depletion **(ADP fossil) [MJ]**
	ReCiPe 2016 v1.1 Midpoint (H) - Fossil depletion **[kg oil eq.]**
	ReCiPe 2016 v1.1 Endpoint (H) - Fossil depletion [$]
Acidification	CML2001 - Jan. 2016, Acidification Potential **(AP) [kg SO_2 eq.]**
	ReCiPe 2016 v1.1 Midpoint (H) - Terrestrial Acidification [**kg SO_2 eq.]**
	ReCiPe 2016 v1.1 Endpoint (H) - Terrestrial Acidification **[species.yr]**
Climate Change	CML2001 - Jan. 2016, Global Warming Potential **(GWP 100 years) [kg CO_2 eq.]**
	ReCiPe 2016 v1.1 Midpoint (H) - Climate change, incl biogenic carbon **[kg CO_2 eq.]**
	ReCiPe 2016 v1.1 Endpoint (H) - Climate change Freshw Ecosystems, incl biogenic carbon **[species.yr]**
	ReCiPe 2016 v1.1 Endpoint (H) - Climate change Human Health, incl biogenic carbon **[DALY]**
	ReCiPe 2016 v1.1 Endpoint (H) - Climate change Terrest Ecosystems, incl biogenic carbon **[species.yr]**
Ozone Layer Depletion	CML2001 - Jan. 2016, Ozone Layer Depletion Potential **(ODP, steady state) [kg R11 eq.]**
	ReCiPe 2016 v1.1 Midpoint (H) - Stratospheric Ozone Depletion **[kg CFC-11 eq.]**
	ReCiPe 2016 v1.1 Endpoint (H) - Stratospheric Ozone Depletion **[DALY]**
Photochemical Ozone Formation	CML2001 - Jan. 2016, Photochem. Ozone Creation Potential **(POCP) [kg Ethene eq.]**
	ReCiPe 2016 v1.1 Midpoint (H) - Photochemical Ozone Formation, Ecosystems **[kg NOx eq.]**
	ReCiPe 2016 v1.1 Midpoint (H) - Photochemical Ozone Formation, Human Health **[kg NOx eq.]**
	ReCiPe 2016 v1.1 Endpoint (H) - Photochemical Ozone Formation, Ecosystems **[species.yr]**
	ReCiPe 2016 v1.1 Endpoint (H) - Photochemical Ozone Formation, Human Health **[DALY]**

4.1.2. Characterization

In the characterization step of LCA, modelled environmental impacts are revealed as environmental impact scores in related reference units for each environmental impact categories. On the next paragraphs, characterization results in midpoint (H) and endpoint (H) characterization on ReCiPe 2016 v1.1 and midpoint characterization on CML2001 - Jan. 2016 LCIA methodologies were evaluated. H symbol on ReCiPe midpoint and endpoint indicators on the above Table 4.1 symbolizes reliability and ability to make short/long term decisions.

The midpoint and endpoint results in ReCiPe 2016 v1.1 methodology and midpoint results in CML2001 – Jan. 2016 methodology have been shown on the next figures (Figure 4.7, 4.8, 4.9, 4.10, 4.11 and Figure 4.12) for the scenarios of plastic packaging materials for each country of Turkey, Italy and Spain. Three of the figures (Figure 4.9, 4.10 and Figure 4.12) have indicated the scenarios of different packaging materials, while including processes of scenarios and specific environmental impact results of each process. According to these figures, midpoint environmental impact characterization of CML2001 - Jan. 2016, Abiotic Depletion (ADP fossil) [MJ] has become the remarkable impact category among the six CML2001 - Jan. 2016 midpoint methodology categories chosen previously. Also, ReCiPe 2016 v1.1 Midpoint (H) - Climate change, incl biogenic carbon [kg CO_2 eq.] has been the most remarkable environmental impact result among the seven related environmental impact categories determined for this study. However, their direct comparison by looking results is not possible since these categories chosen for this study have been in different reference units for different methodologies of CML and ReCiPe. So, their comparison requires a further step of normalization & weighting, which can give unitless results and relative significance of these group of results for each methodology. The figures related to impact results of ReCiPe 2016 v1.1 midpoint (H) and endpoint (H) categories can be seen on the next pages for all scenarios (Figure 4.7 and Figure 4.8).

4.1.2.1. Climate change. This indicator is correlated with the increase in global temperature in average that stems from greenhouse gas emissions (GHG). The major contributor has been the combustion processes of fossil fuels such as natural gas, oil and coal. The global warming potential of GHG has been measured in kilogram of carbon dioxide equivalent (kg CO_2 eq) (European Commission, 2024) for the midpoint impact categories of CML and ReCiPe methodologies. For the endpoint climate change categories of ReCiPe, the unit are divided into three which are related to human health, terrestrial ecosystems and freshwater ecosystems. Human health is associated with [DALY] (disability adjusted life years) unit, which shows life loss in years and time being disabled

by increased diseases or natural disasters due to increased average global temperature in years. For terrestrial ecosystem, damage pathway is indicated as loss of species regarding the change in distribution of biome and global average temperature increase in the unit of [species.year]. For the freshwater ecosystems, fish loss was considered as damage pathway regarding the river discharge decrease in the unit of [species.year] (Huijbregts et al., 2017).

By considering the figures of Figure 4.7 and Figure 4.8, it can be seen that impact category of ReCiPe 2016 v1.1 midpoint (H) - climate change (kg CO_2 eq.) has diminished by 2050 scenarios for the two European countries when current scenarios of packaging materials have been observed. For PP, climate change scores were decreased by 17.2% and 47.1% for Spain and Italy; for PE, the scores of climate change were decreased by 17.4% and 47.3% for Spain and Italy; the scores were decreased for PS, 18.2% and 45.5% and for PET, 18.8% and 40.3% in Spain and Italy, respectively. In Turkey, when it was investigated the change in between current and 2050 scenarios, the decrease trend is also observable by 22.5% for PP, 33.9% for PE, 25.3% for PS and 45.3% for PET. That decrease trend in Turkey can be associated with increased renewable energy share in Turkish electricity grid utilized in 2050, by regarding Turkey National Energy Plan (Table 3.1). For the countries of Spain and Italy, the reduction of climate change (kg CO_2 eq.) impact results in 2050 have been relevant to decrease in packaging material amount by 25%, when the current scenarios and 2050 scenarios of two countries are compared (Table 3.1). The packaging material reduction share of 25% was determined with respect to target of reducing packaging material in Europe.

From current scenarios to 2030 scenarios, trend of increase can be observed which is related to rise in incineration share in 2030 scenarios. For example, in Turkey, the climate change impact category scores were significantly increased, by 47.6% for PE material and 45.6% for PS material and 30.5% for PET material. In Italy and Spain, similar increases can be observed for PE, PS, PP and PET, too. For example, in the life cycle of PE material, climate change impact scores were increased by 34.3% and 9.34% in Spain and Italy. Rather than landfill, recycling and energy recovery/incineration options were employed in 2030 scenarios with different shares as can be seen on Table 3.1, in Materials and Methods section. The emissions from landfill for the environmental impact category of climate change have not had a directly outcome similar to energy recovery/incineration option which directly emits CO_2. Incineration process has had direct emissions of CO_2, so climate change impact category has increased with burden of CO_2 during incineration process.

Current situation scenarios of PET have had a bigger impact result on midpoint (H) - climate change (kg CO_2 eq.) category among the other scenarios of packaging materials of PP, PE, and PS. It can be correlated with the complex production processes of PET material, including ethylene oxide and paraxylene production. The other materials have had less complex production steps that require less chemical material like polyolefin group of PP, PE or PS. Also, Italy has had bigger impact scores in this environmental impact category. For the scenario of current situation of PET in Italy, the contribution of only this scenario to the climate change impact characterization result has been 4.67% among 36 scenarios. In Italy, the climate change characterization result was highest when compared to other scenarios. Figure 4.9 has been prepared for current scenario of Italy for PET. It can be concluded that the Figure 4.9 have indicated the additional environmental impact of ethylene oxide and paraxylene production processes in midpoint (H) - climate change impact category. High electricity consumption in these production stages specific for PET life cycle, have been contributed to the climate change characterization result of PET life cycle. Polyethylene waste incineration and plastic injection molding process have had also high amounts of climate change CO_2-eq contributions when the Figure 4.9 is observed. Incineration process with intensive CO_2 emissions and injection molding process with high electricity consumption can be associated with high environmental impact scores in this environmental impact category (Elduque et al., 2015; Tiwari et al., 2023). However, all of the packaging materials and countries have had incineration and injection moulding shares consisting in their scenarios, so this cannot be a criteria to evaluate this high amount of CO_2-eq for PET. Situation of current Italy – PET scenario can also be linked to usage of Italy electricity grid that has lower renewable energy share (39.93%) rather than Turkey, has 41.51% renewable share in related electricity grid mix and Spain, which has 47.51% of renewable share, as it is shown on Figure 2.15, Figure 2.16 and 2.17 previously. The renewables chosen for electricity generation have also led to different environmental impacts and non-renewable sources used in electricity generation can also lead to different impact results too, while making the comparison of Spain and Turkey in the current situation scenarios of packaging materials. High shares of wind power, and a share of photovoltaic power in Turkey 2022 grid mix (Figure 2.15) lead to a more environmentally friendly impact score, when the Spain electricity grid mix used in this study is considered.

4.1.2.2. Fossil depletion. Fossil depletion (or resource use) impact category was related to usage of finite amount of non-renewable resources. While fossil fuels such as coal, gas and oil have been extracting today, future generations are not able to extract these resources, force to find new resources or able to extract them in less amount. Materials that are associated with resource use is converted into MJ for CML2001 – Jan.2016 methodology (European Commission, 2024), kg oil eq.

for ReCiPe 2016 v1.1 midpoint impact category and [$] for ReCiPe endpoint category. Kg oil eq. is correlated with the value of fossil resource for higher heating and the content of energy in crude oil, for midpoint impact in ReCiPe. Unit of [$] for ReCiPe endpoint fossil resource scarcity which is correlated with increase in cost because of increased fossil extraction. It generally shows the increased costs for future practices in mineral and fossil extraction (Huijbregts et al., 2017).

For ReCiPe 2016 v1.1 endpoint (H) results, environmental impact category of fossil depletion [$] have had decrease trends by years. For life cycle of PS material in Turkey, Spain and Italy, decreases of 42.2%, 24.3% and 22% were observed in 2050 scenarios, when it was considered current scenarios. For 2030, decreases by 6.72% and 3.97% in Spain and Italy; and a small increase by 5.81% in Turkey were also observed. For Turkey, a sudden increase in the incineration share in current scenario (Table 3.1) could have been resulted this small increase. For the life cycles of other materials of PP, PE, and PET, the results have followed the same trend for three countries. In detail, for 2030 Turkey fossil depletion impact result were slightly increased, and then has followed a decrease for 2050. For Spain and Italy, small decreases in 2030 and higher amount of decreases in 2050 were observed in results. In 2050 scenarios of each packaging material has had a relatively small impact result on fossil depletion [$], with the improvements on increased renewable energy share in Turkey electricity grid utilized and packaging material reduction in Europe countries of Italy and Spain. By decreasing non-renewable resources usage while producing electricity grid in Turkey, fossil depletion can become smaller. Also, a reduction in production of packaging material, as it is expected, can lead to decrease in the result of fossil depletion [$] impact category. When packaging material are produced less, the need on crude oil resources also become less. The unit of [$] in fossil depletion impact category has indicated the increased costs for extraction of fossil – mineral resources, within cost-tonnage relationship. Damage pathway in this impact category has “increased extraction costs” and has led to damage to resource availability as an endpoint area of protection (Huijbregts et al., 2017).

Impact scores of fossil depletion endpoint impact category for polypropylene has had a bigger impact score than PET, PP and PS materials in all scenarios. Even the lowest impact score of fossil depletion of polypropylene material in ES – 2050 PP scenario, has had a higher score than the impact scores of other packaging materials. This can be related to dependence of polypropylene material on fossil resources. As it can be observed on the Figure 4.10, the need for crude oil in polypropylene material life cycle have been higher than other packaging materials. Especially for the current scenario of PP material in Italy, fossil depletion [$] category contributes the overall impact score in 5.07% when considered the other 35 scenarios. Crude oil production stage of

polypropylene was required a higher amount of crude oil in material's life cycle and, considering the other packaging materials PP has the highest dependency on crude oil with its propylene production stage, according to life cycle inventory analysis. Rather than PE packaging material, PP material has had the most nonrenewable resource-dependent life cycle, by requiring high amount propylene which is only specific for life cycle of PP. Life cycles of PE, PS and PET packaging materials have not had this kind of high requirement for crude oil, when the results in life cycle inventory analysis were considered. Also, the electricity grid mix used in Italy without a future improvement in scenario (Table 3.1), has led to this high score.

4.1.2.3. Acidification. Acidification is correlated to the fish mortality and decrease in forest amount with coniferous. This can be related to emissions carried to air, water and soil. Combustion processes during the production of electricity and heat, transporting have become the major sources for acidification. Sulphur containing fuels are associated with higher contribution for the impact category of acidification. It can be converted to hydrogen cation (H^+) (European Commission, 2024). The unit of [kg SO_2 eq.] is acceptable for CML2001 – Jan.2016 impact category of acidification potential and for ReCiPe midpoint impact category of terrestrial acidification. Pollutant fate in the atmosphere and soil are specified as midpoint characterization factors. Acid deposition and air emission changes related to sulfur dioxide (SO_2), nitrous oxides (NOx), and ammonia (NH_3) were calculated with these characterization factors. For ReCiPe endpoint impact category of terrestrial acidification, the unit of [species.yr] is specified. Plant species loss because of pH decline in soil is associated with unit of [species.year] to observe density of species (Huijbregts et al., 2017).

For the acidification potential in ReCiPe impact categories, the results of current scenarios were followed a trend of increase when compared to 2030 scenarios for packaging materials. For 2050 scenarios, a significant decrease regarding current scenarios was observed for terrestrial acidification [kg SO_2 eq.] midpoint impact category in ReCiPe. The highest contributor for this impact category result has become the scenario of Turkey in 2030 for PP life cycle, when overall characterization result in ReCiPe terrestrial acidification midpoint impact category is considered. The overall midpoint impact score of terrestrial acidification for all scenarios was 63.407 kg SO_2-eq and the scenario of 2030 in Turkey for PP was contributed this overall score in 4.43%, among 36 scenarios. For the endpoint category of terrestrial acidification [species.yr], the highest result was marked for PP – Turkey scenario in 2030, again. The overall endpoint characterization result for terrestrial acidification [species.yr] was 1.36×10^{-5} species.yr and the PP 2030 – Turkey scenario has a contribution of 4.39%. As it was mentioned above, heavily fossil fuel combustion or

production of electricity can be correlated to this high score. PP is previously mentioned as crude-oil intensive process with its production stages, requiring high amount of petroleum products, as it can be seen on Figure 4.1, created figure via GaBi software for midpoint impact category. It can be also observed Figure 4.2 which belongs to endpoint result of terrestrial acidification [species.yr], specifically. There can be seen that processes of idealized injection molding for PP and olefin production which consumes crude oil have had higher impact result by contributing more than half to the total scenario result. High energy-consuming process of injection molding has been associated with this result, with the process of olefin production that consumes crude oil (Elduque et al., 2015). Elduque et al. (2015) has mentioned that injection molding processes are electric-consuming processes and electricity consumption are known as the most relevant factor for environmental impact scores. In their study (2015), it was also indicated that environmental impacts of injection molding processes had been high due to solvent usage during the application. Also, for the scenarios of other countries in 2030, the packaging material amounts were lowered and kg of molded plastics were also lowered. For the other causes of the high result can be associated with raised incineration share in Turkey - 2030 scenario as it can be seen on Table 3.1. For other PP – 2030 scenarios in Italy and Spain, incineration shares were already included in scenarios of current situation, so a high result originated by a sudden raise can not be observed.

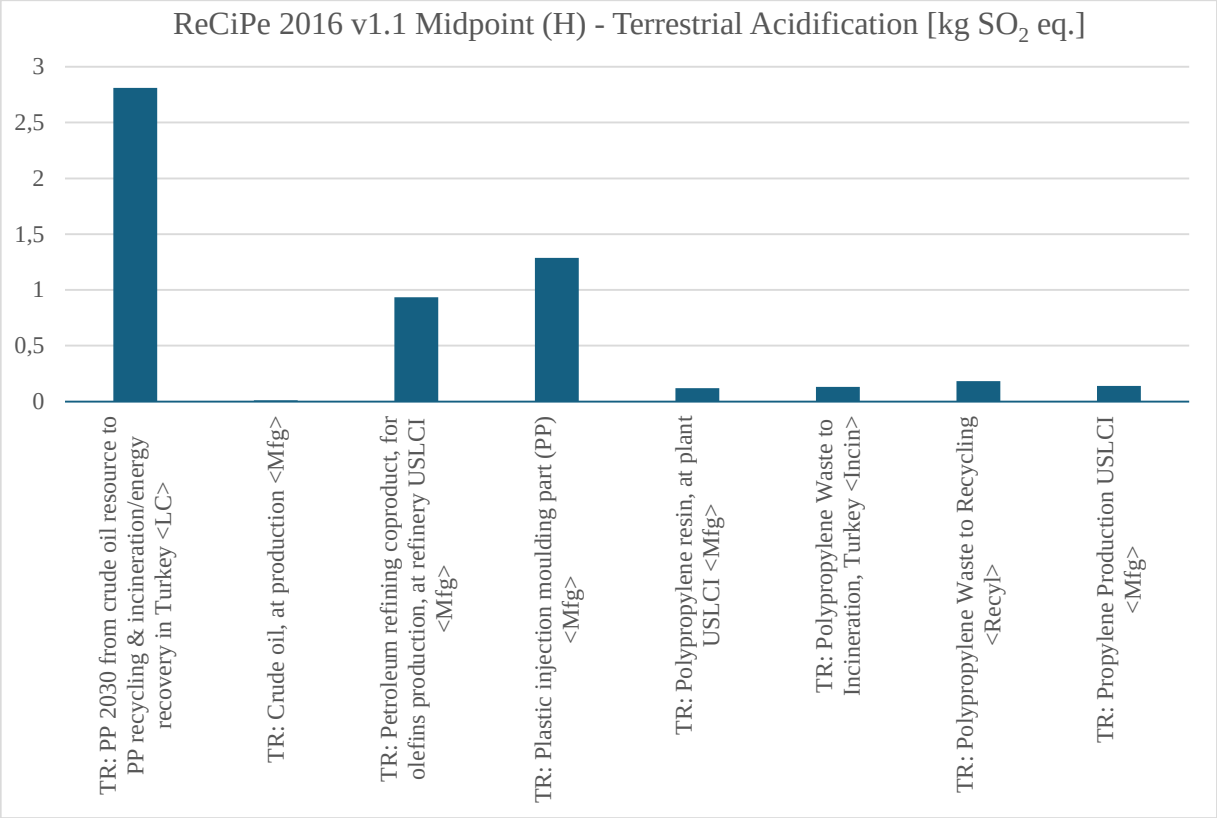

Figure 4.1. Terrestrial Acidification [kg SO_2 eq.] midpoint (H) result for the scenario of PP – 2030 for Turkey.

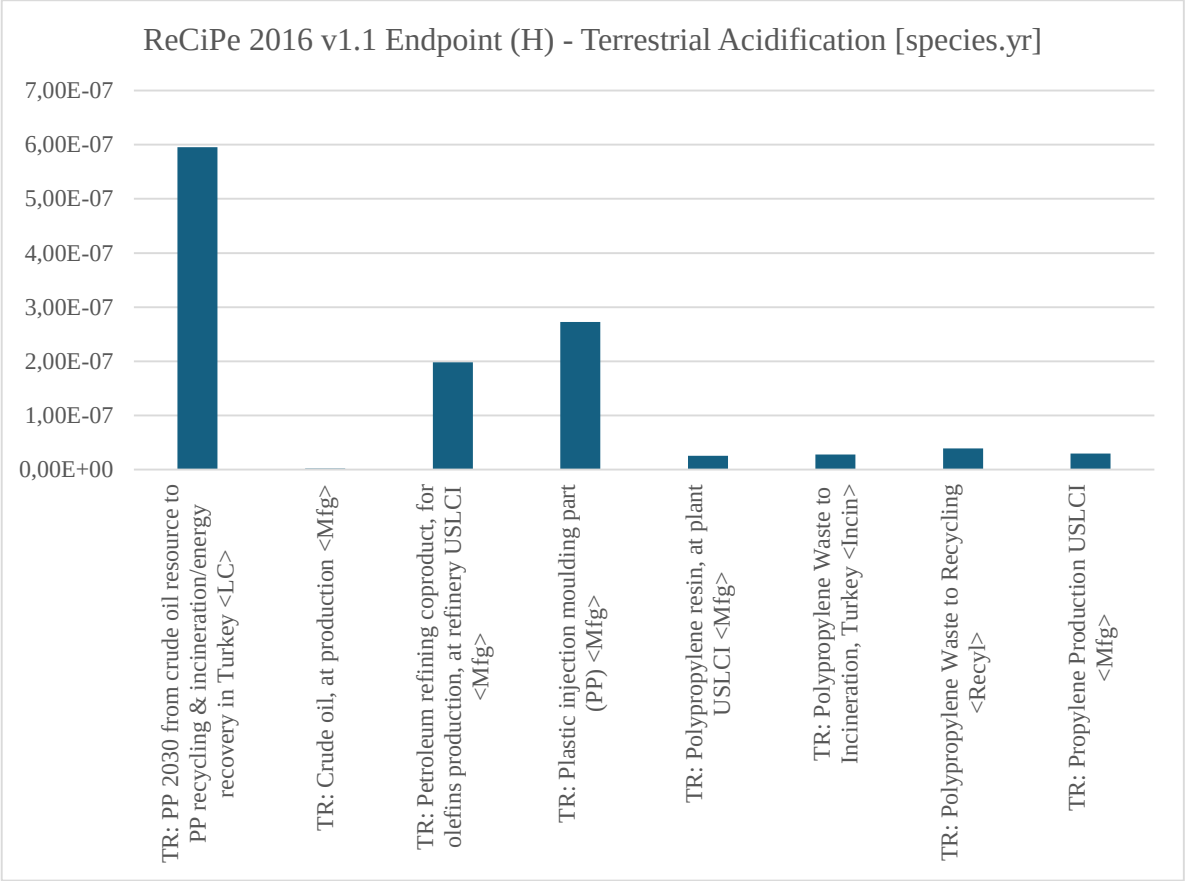

Figure 4.2. Terrestrial Acidification [species.yr] endpoint (H) result for the scenario of PP – 2030 for Turkey.

4.1.2.4. Ozone layer depletion. Reaching of UV-B ultraviolet radiation to the Earth is prevented by the presence of stratospheric ozone layer of O3. Stratosphere is a layer of atmosphere and has a 15-50 km height from the Earth ground. When the stratospheric ozone layer is depleted, humans can be faced with skin cancer cases and plants are also be damaged. Impacts of the substances associated with ozone depletion have converted to kilogram equivalent of trichlorofluoromethane (European Commission, 2024). Stratospheric ozone depletion with the unit of [kg R11 eq.] for CML impact category and [kg CFC-11 eq.] for ReCiPe midpoint impact category are related to same chemical compound, R11 and CFC-11 are symbolized to show chemical compound of trichlorofluoromethane. So, these two impact categories are in same unit. For ReCiPe endpoint impact category with the unit of [DALY], it is indicated that human health is concerned to harm, due to reduction in the stratospheric ozone. This was explained as ozone depletion causing UV-B radiation to increase and increased UV-B radiation led to diseases which is included in the unit of DALY, disability adjusted life years. Skin cancers and cataract associated with UV-B radiation have been consisted in the endpoint impact category of ReCiPe (Huijbregts et al., 2017).

For the ReCiPe midpoint impact category of Stratospheric ozone depletion [kg CFC-11 eq.], the highest impact result was belonging to current situation scenario of Italy for the life cycle of polyethylene material. While the total midpoint characterization result for stratospheric ozone depletion [kg CFC-11 eq.] was 0.0109 kg CFC-11 eq., the contribution of current Italy PE scenario was 4.2% among all scenarios. And as it was obtained in the terrestrial acidification impact category, plastic injection molding process was contributed in highest amount to the scenario characterization result on Figure 4.3. For the ReCiPe endpoint impact category of stratospheric ozone depletion [DALY], the current situation scenario of Italy for PE life cycle was represented the highest score, by contributing 4.24% to the total endpoint stratospheric ozone depletion characterization result of 5.79 x 10^{-6} DALY. And, process of plastic injection has had the highest contribution amount to the total scenario characterization, as it is seen on Figure 4.4. Again, study of Elduque et al. (2015) can be considered, when plastic injection results are observed with highest/higher contribution.

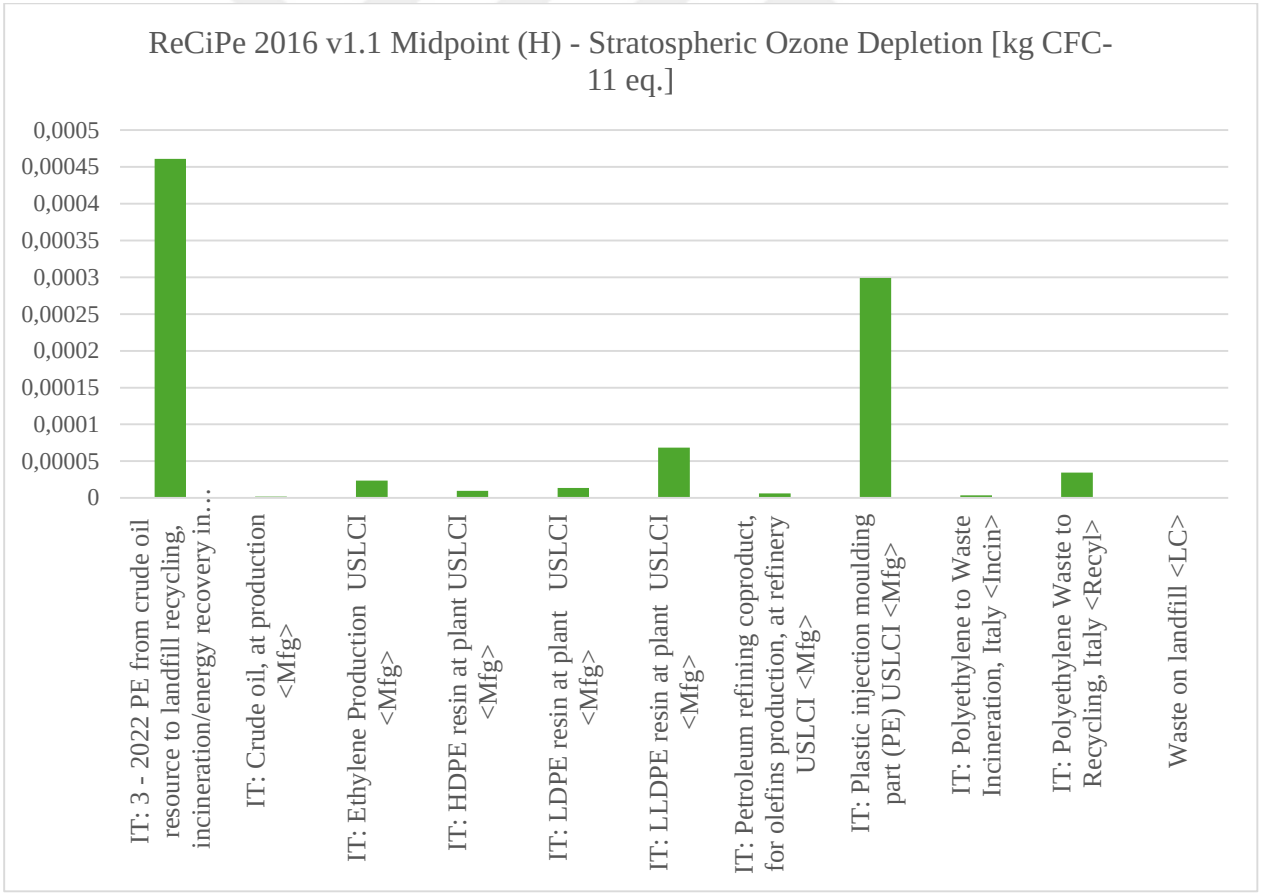

Figure 4.3. Stratospheric Ozone Depletion [kg CFC-11 eq.] midpoint (H) result for the scenario of PE – current situation for Italy.

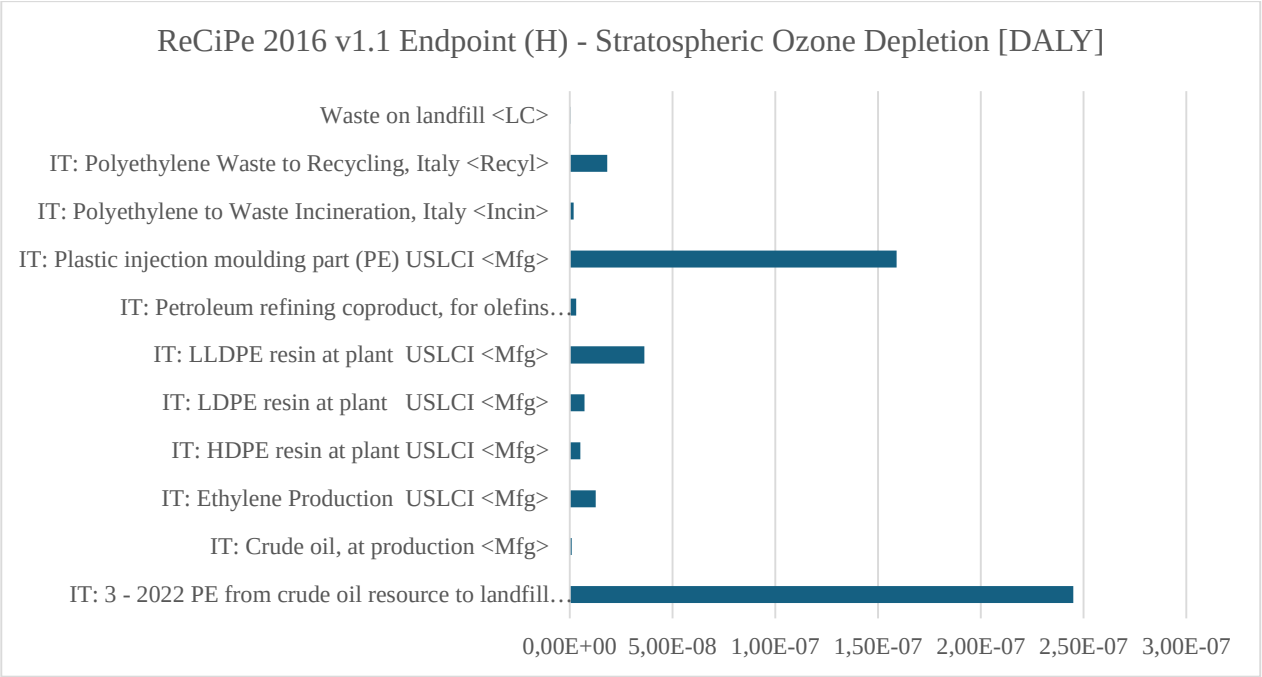

Figure 4.4. Stratospheric Ozone Depletion [DALY] endpoint (H) result for the scenario of PE – current situation for Italy.

4.1.2.5. Photochemical ozone formation. While ozone molecule (O_3) prevents Earth from harmful radiation of ultraviolet, ozone molecule on the troposphere, which is a layer of atmosphere closest to the ground. It can harm organic tissue in plants and animals. Photochemical smog is also created by increased ozone amount in the ground. Substances related to photochemical ozone formation is transformed into non-methane volatile organic compounds in kilogram equivalent. Alcohols or aromatic compounds are also able to perform as a unit for conversion (European Commission, 2024). After the pollutant related to photochemical ozone formation was released, change in ozone amount in ground was calculated according to the characterization factors. For CML2001 – Jan.2016 impact category, the unit is defined as [kg Ethene eq.]. For ReCiPe midpoint impact categories of photochemical ozone formation, ecosystems [kg NO_x] and photochemical ozone formation, human health [kg NO_x eq.] have been in the same unit. The ReCiPe endpoint impact categories of photochemical ozone formation, ecosystems [species.yr] and photochemical ozone formation, human health [DALY] have different units. [DALY] unit has been indicated the life years loss by looking the damage pathways of respiratory and cardio-related diseases for human health endpoint impact category and plant loss because of rise in ozone molecule amount in the environment (Huijbregts et al., 2017).

For both of ReCiPe midpoint and endpoint impact categories of photochemical ozone formation with [kg NOx] and [DALY] units, the highest contribution was caused by current

situation scenario in Spain for PET. ReCiPe 2016 v1.1 Midpoint (H) - photochemical ozone formation, ecosystems [kg NOx eq.] and human health [kg NOx eq.] impact categories were appeared as 5.3% and 4.9% contribution shares of total characterization scores of 67.65 kg NOx-equivalent and 58.64 kg NOx-equivalent. For endpoint categories of photochemical ozone formation, ecosystems [species.yr] and photochemical ozone formation, human health [DALY], Spain current scenario for PET material were calculated as 5.2% of 4.65 x 10^{-7} species.year and 4.8% of 2.59 x 10^{-6} DALY, respectively (Figure 4.6). Ethylene oxide production process, as can be seen on Figure 4.5, was contributed in highest amount to the midpoint impact categories in 39.8% and 31.6% for photochemical ozone formation, ecosystems [kg NOx eq.] and human health [kg NOx eq.], respectively. The process of ethylene oxide production was contributed in highest amount for endpoint categories of photochemical ozone formation, ecosystems [species.yr] and photochemical ozone formation, human health [DALY] in 39.8% and 31.6% respectively. Ethylene oxide is a VOC chemical and ozone molecule can be generated by oxidation reaction of sunlight and chemicals of VOCs and NOx, according to the Jenkin et al. (2017). In the study (2017), it was specified that precursors of VOCs and NOx have been the emissions to be controlled in order to reduce ozone levels during photochemical pollution periods (Jenkin et al., 2017). In another study of Zou et al. (2023), it was revealed that VOC species have been in plentiful amount with their high reactivity, and photochemical reactions they performed during emissions are underestimated (Zou et al., 2023)

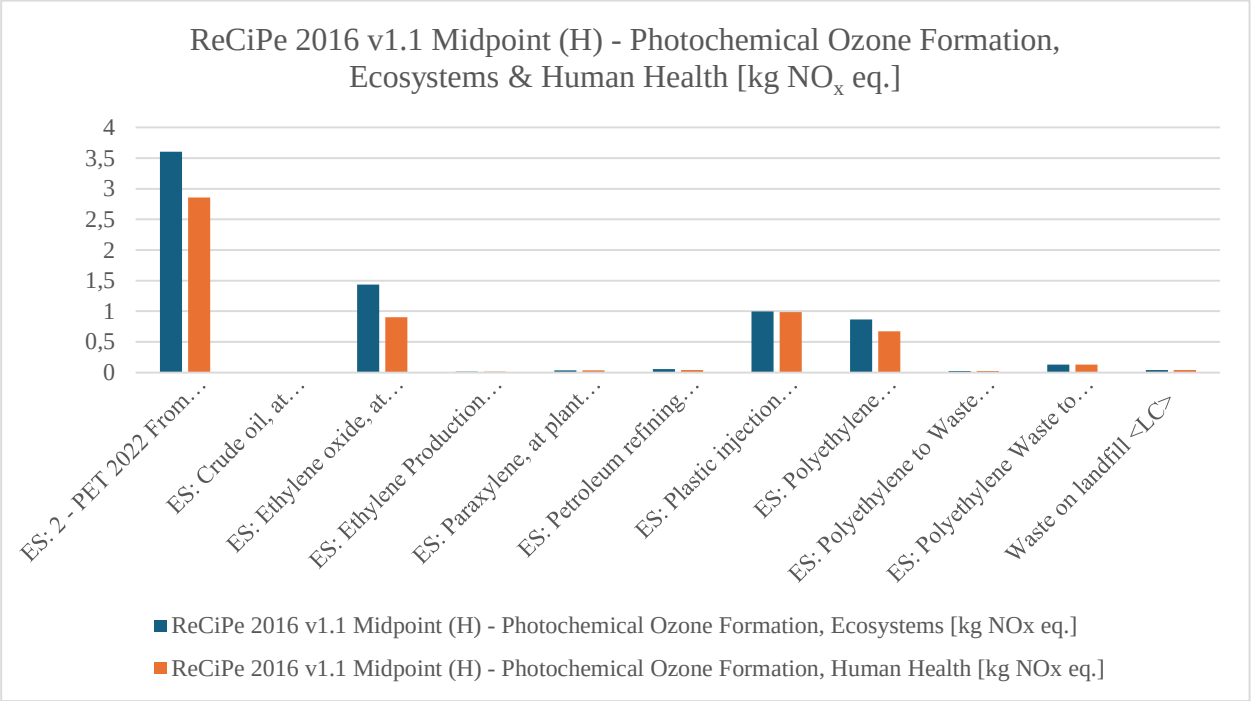

Figure 4.5. Photochemical Ozone Formation, Ecosystems and Human Health [kg NO_x eq.] midpoint (H) results for current scenario of PET in Spain.

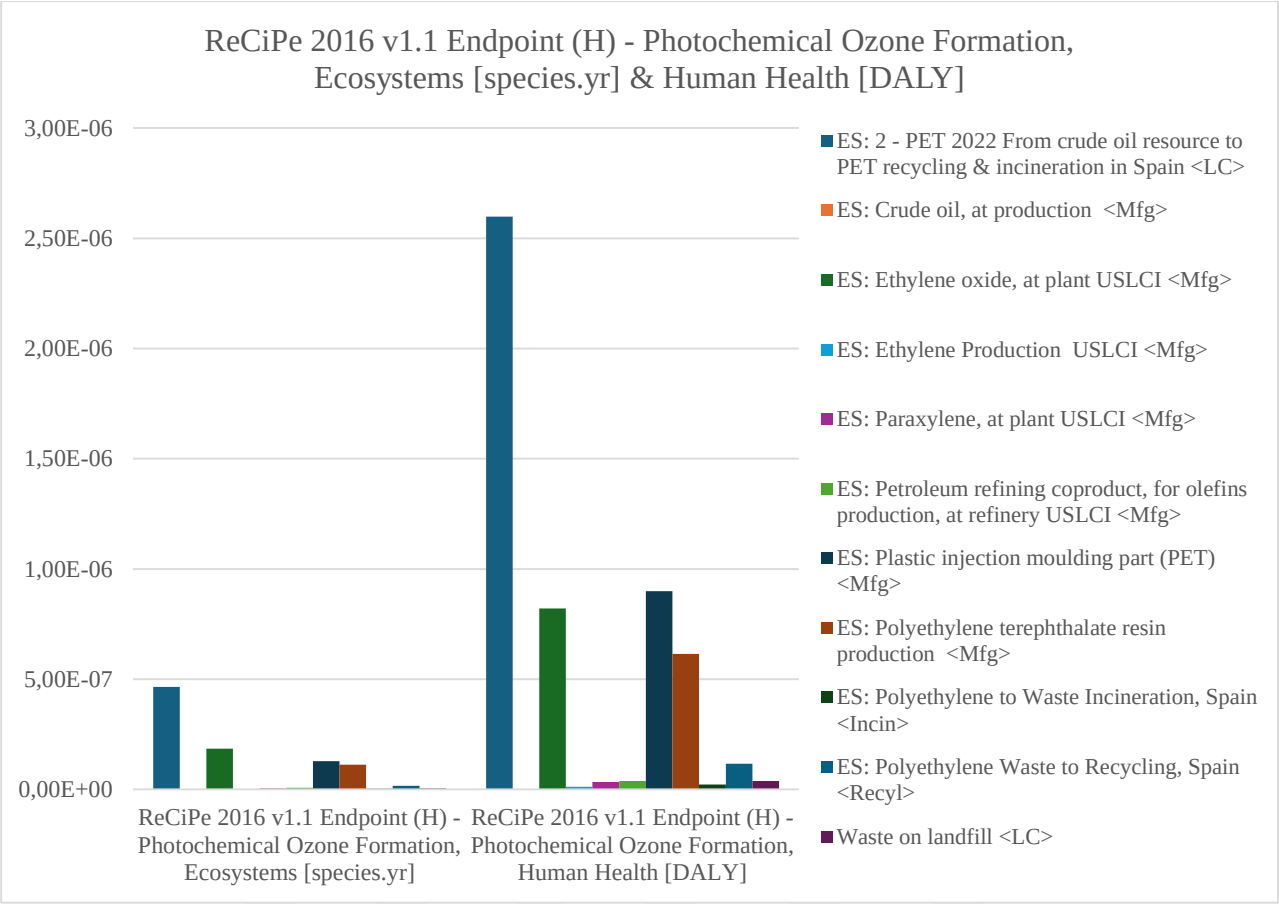

Figure 4.6. Photochemical Ozone Formation, Ecosystems [species.yr] & Human Health [DALY] endpoint (H) results for current scenario of PET in Spain.

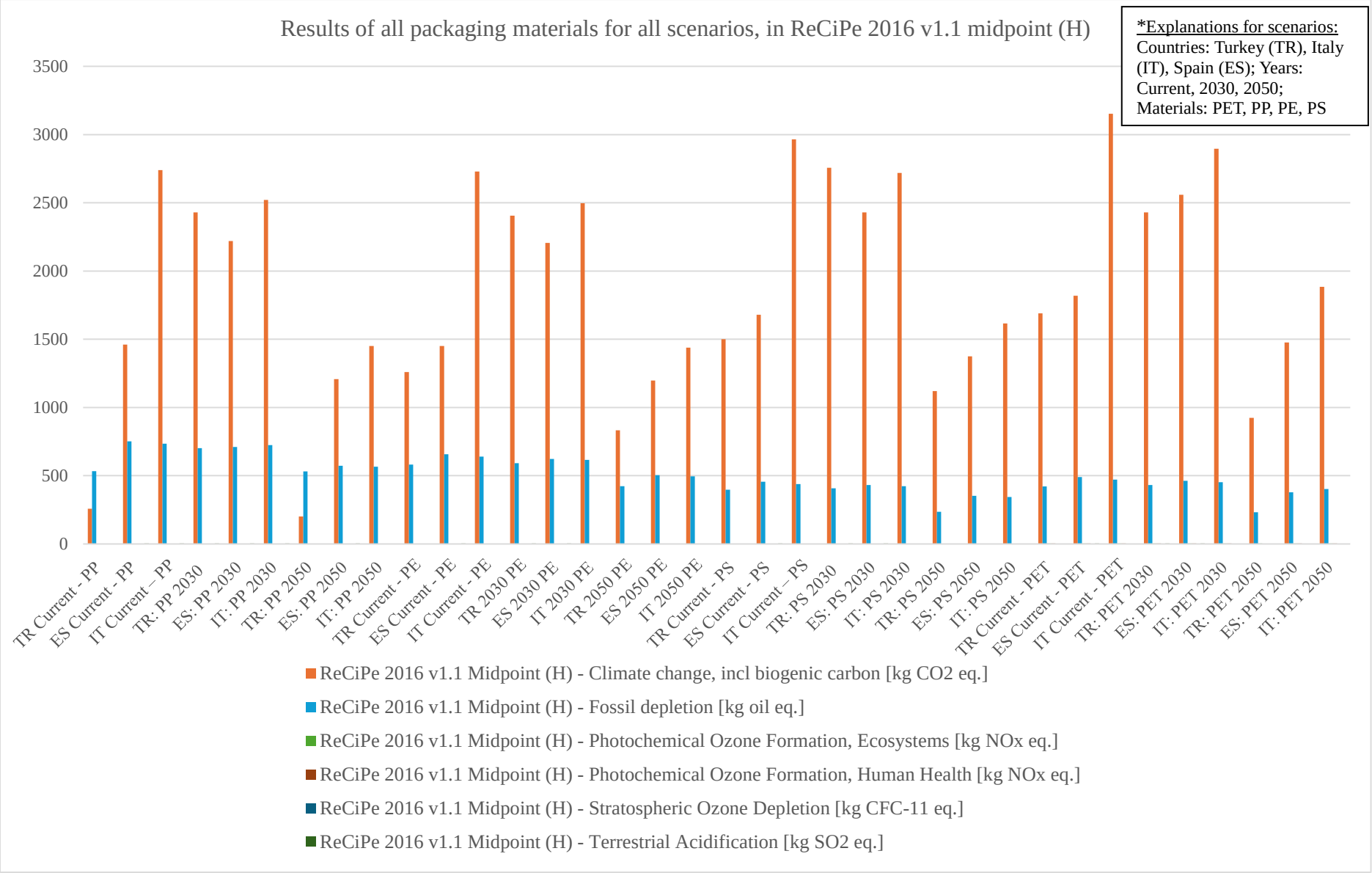

Figure 4.7. Results of PE, PP, PET and PS packaging materials for all scenarios, in ReCiPe 2016 v1.1 midpoint (H).

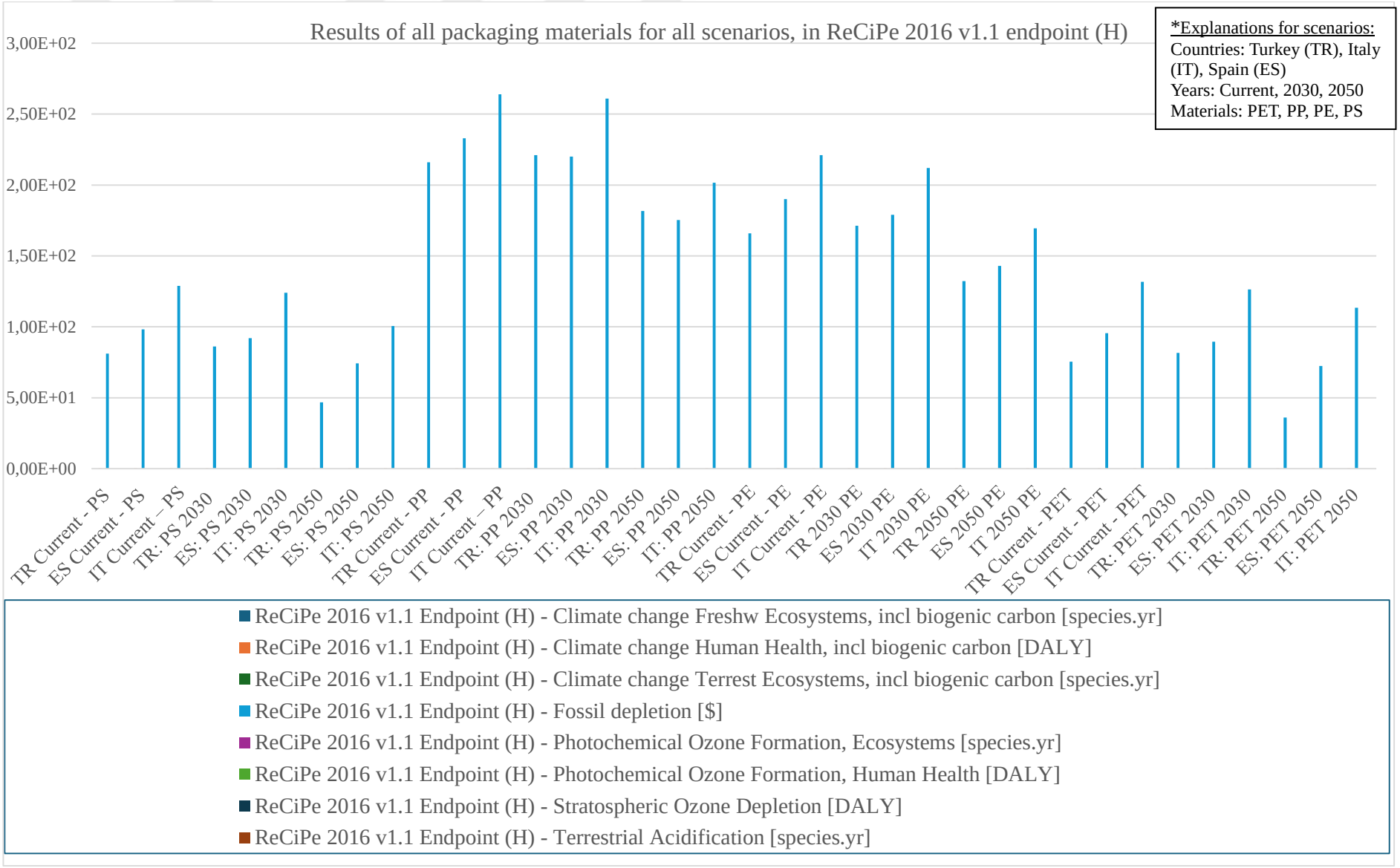

Figure 4.8. Results of PE, PP, PET and PS packaging materials for all scenarios, in ReCiPe 2016 v1.1 endpoint (H).

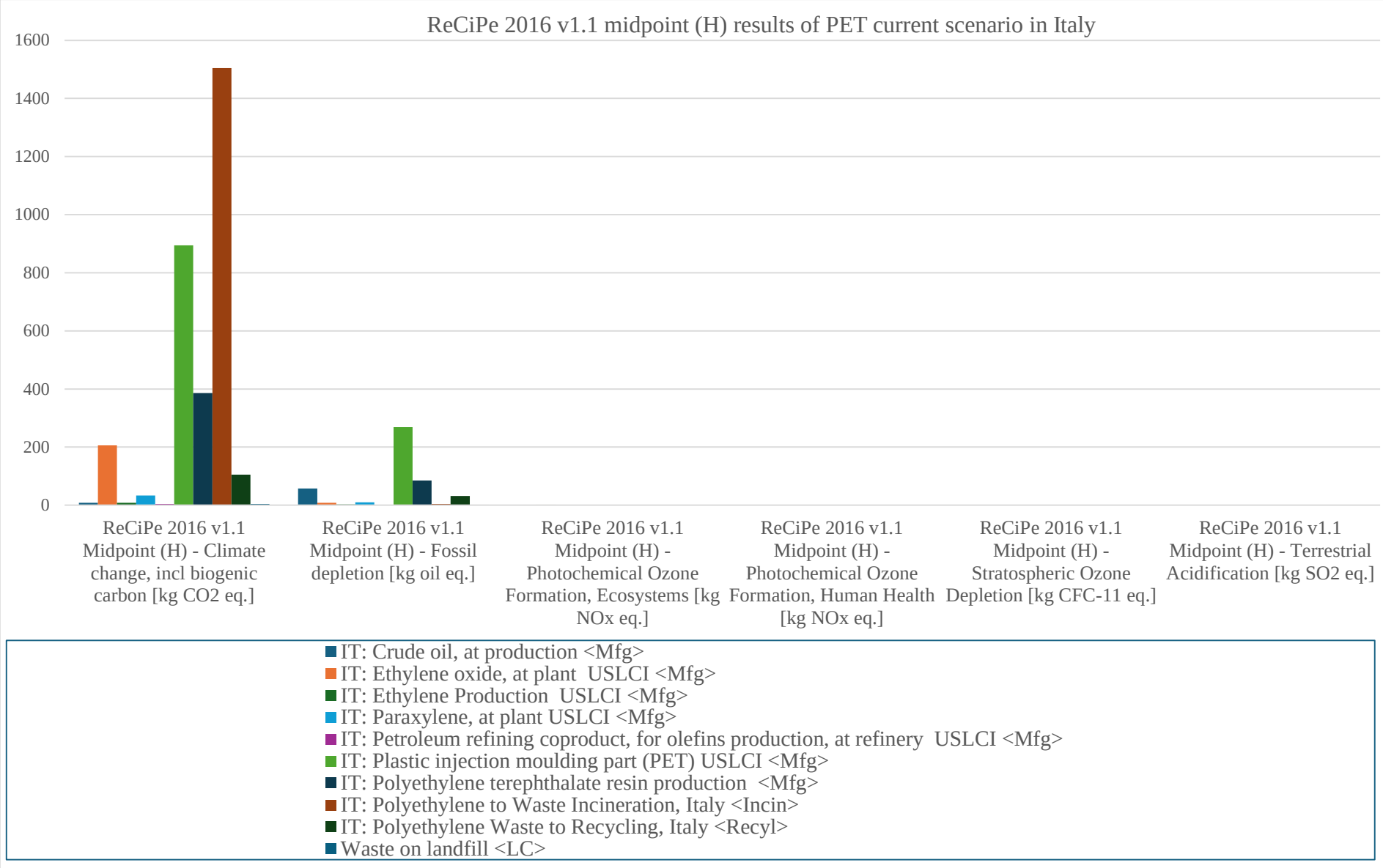

Figure 4.9. ReCiPe 2016 v1.1 midpoint (H) results of PET current scenario in Italy, with processes comprised.

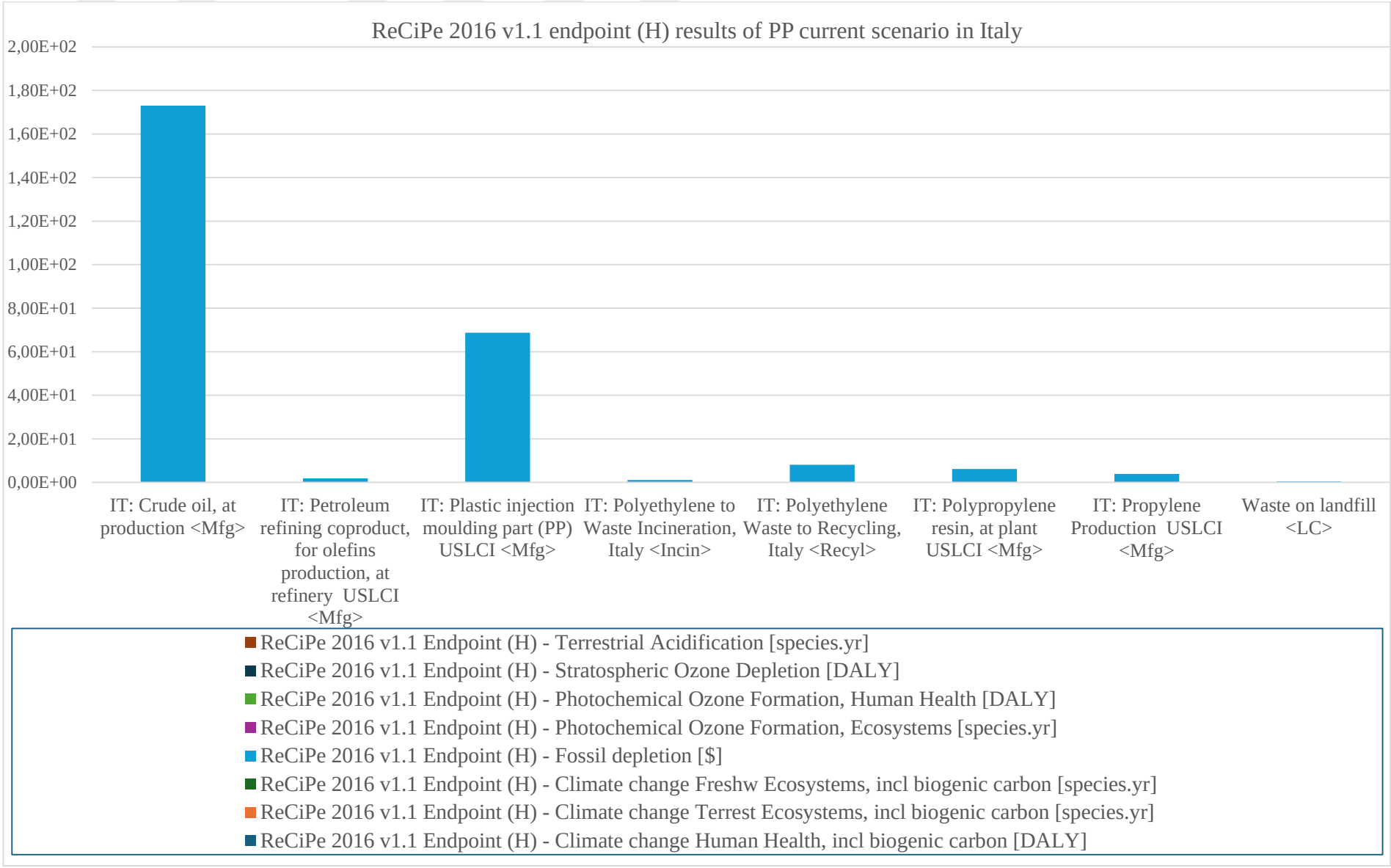

Figure 4.10. ReCiPe 2016 v1.1 endpoint (H) results of PP current scenario in Italy, with processes comprised.

For CML 2001 – Jan. 2016 midpoint impact category results, Figure 4.11 and 4.12 can also be observed. Environmental impact category result of CML2001 - Jan. 2016, Abiotic Depletion (ADP fossil) [MJ] has had a remarkable decrease gradually, in the scenarios of 2030 and 2050 for all packaging materials. For PET in 2030 scenarios, 11.2%, 6.6% and 4.1% decrease were observed in the countries of Turkey, Spain and Italy, when it was considered current scenarios of these countries. For 2050 PET scenarios, decreases of 73.7%, 23.8% and 14.7% in the abiotic depletion results were seen for Turkey, Spain and Italy, respectively. For the other materials of PP, PE and PS, CML2001 - Jan. 2016, Abiotic Depletion results were followed the same decrease trends, in which Turkey get the lowest results of abiotic depletion impact category. The gradual reduction can be associated with the renewable energy share increase in Turkish National Energy Plan and decreased usage of packaging materials in European countries of Italy and Spain by reducing packaging material 5% and 25%.

Polypropylene packaging material has had bigger impact result in abiotic depletion impact category while the results of PET, PE and PS material scenarios has had a smaller impact result in CML. The result has been similar to result in ReCiPe 2016 v1.1 endpoint (H) results in fossil depletion [$] impact category. Even though, these two impact categories which belong to different methodologies of CML and ReCiPe, has given different amounts of results with different units; the dependence on fossil resources has highlighted by considering high impact scores in CML methodology among other impact categories of CML. Crude oil production was included in all the packaging material scenarios, but polypropylene's high crude oil consuming process had reflected on these impact scores of abiotic depletion (MJ) and fossil depletion [$] categories, as they can be seen on Figure 4.10 and Figure 4.12. For PE and PP materials, monomers of these polymers have been obtained from crude oil, and not another chemical compound was included in the life cycles of PE and PP, as these can be observed on the tables of Table 3.3 and Table 3.4, which have shown inputs and outputs of the life cycles. When the tables of Table 3.5 and Table 3.6, for PET and PS materials were seen, other chemical compounds such as ethylene-oxide, xylene for PET and benzene for PS were also included in the life cycles. These chemical compounds have been not directly related to crude oil, like ethylene and propylene which require consumption of crude oil.

The other impact categories of CML2001 - Jan. 2016 Acidification Potential (AP) [kg SO_2 eq,], Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq,], and Photochemical Ozone Creation Potential (POCP) [kg Ethene eq, have remarkably followed the trend of decrease similar to results of ReCiPe impact categories, when 2050 scenarios of packaging materials are compared to current scenarios. For acidification potential, highest contributor to the overall AP characterization

result for all scenarios has been the 2030 scenario in Turkey for PP material, with contribution of 4.1% by regarding total 95.46 kg SO_2-equivalent. For ozone layer depletion 2030 scenario in Turkey for PP material has had again the highest contribution in 6% of 9 x 10^{-7} kg R11 equivalent total amount. For photochemical ozone formation impact category, current scenario in Italy for PET material was the highest contributor by 6% share in total characterization score of 21.9 kg Ethene equivalent.

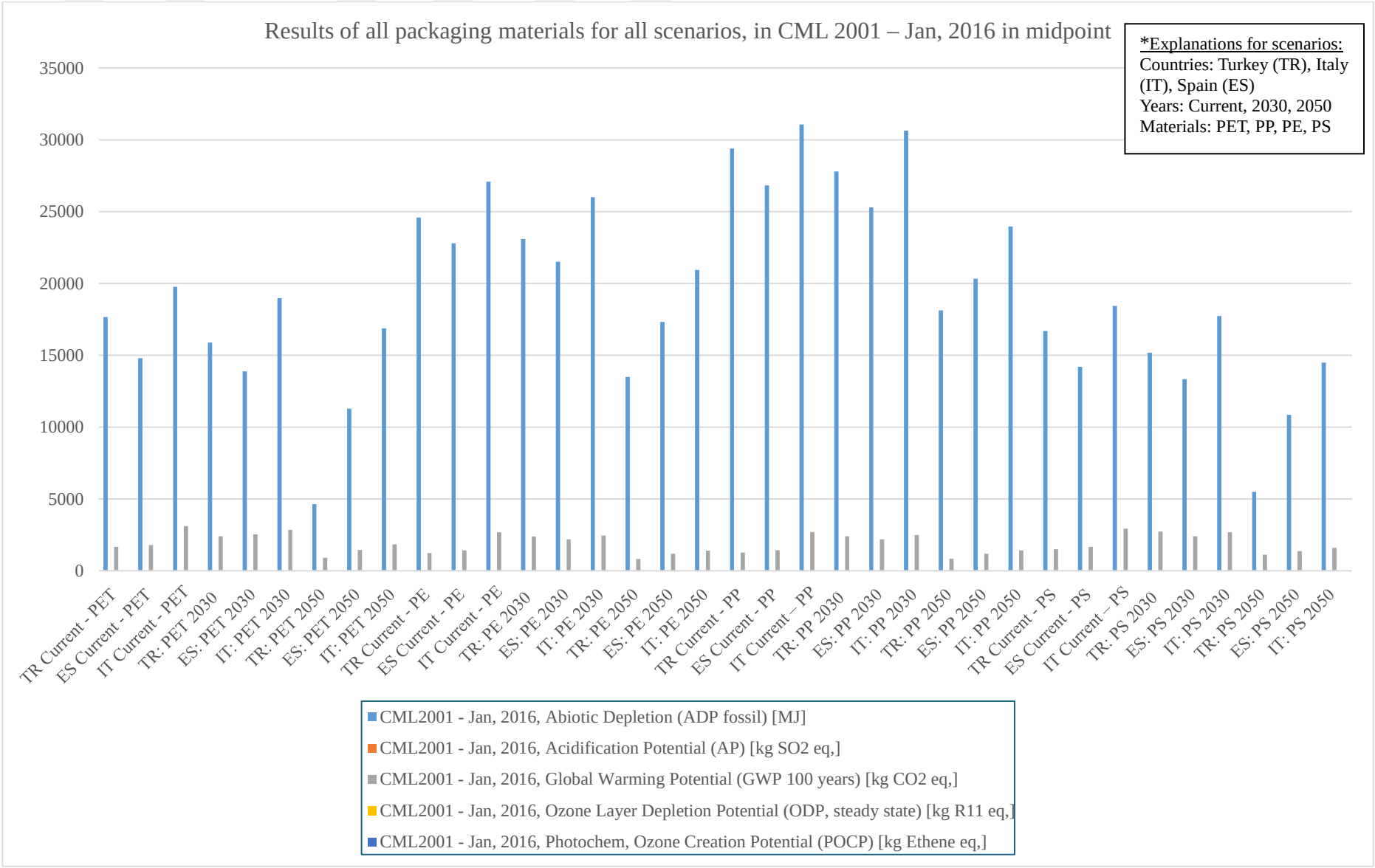

Figure 4.11. Results of PE, PP, PET and PS packaging materials for all scenarios, in CML 2001 – Jan, 2016 in midpoint.

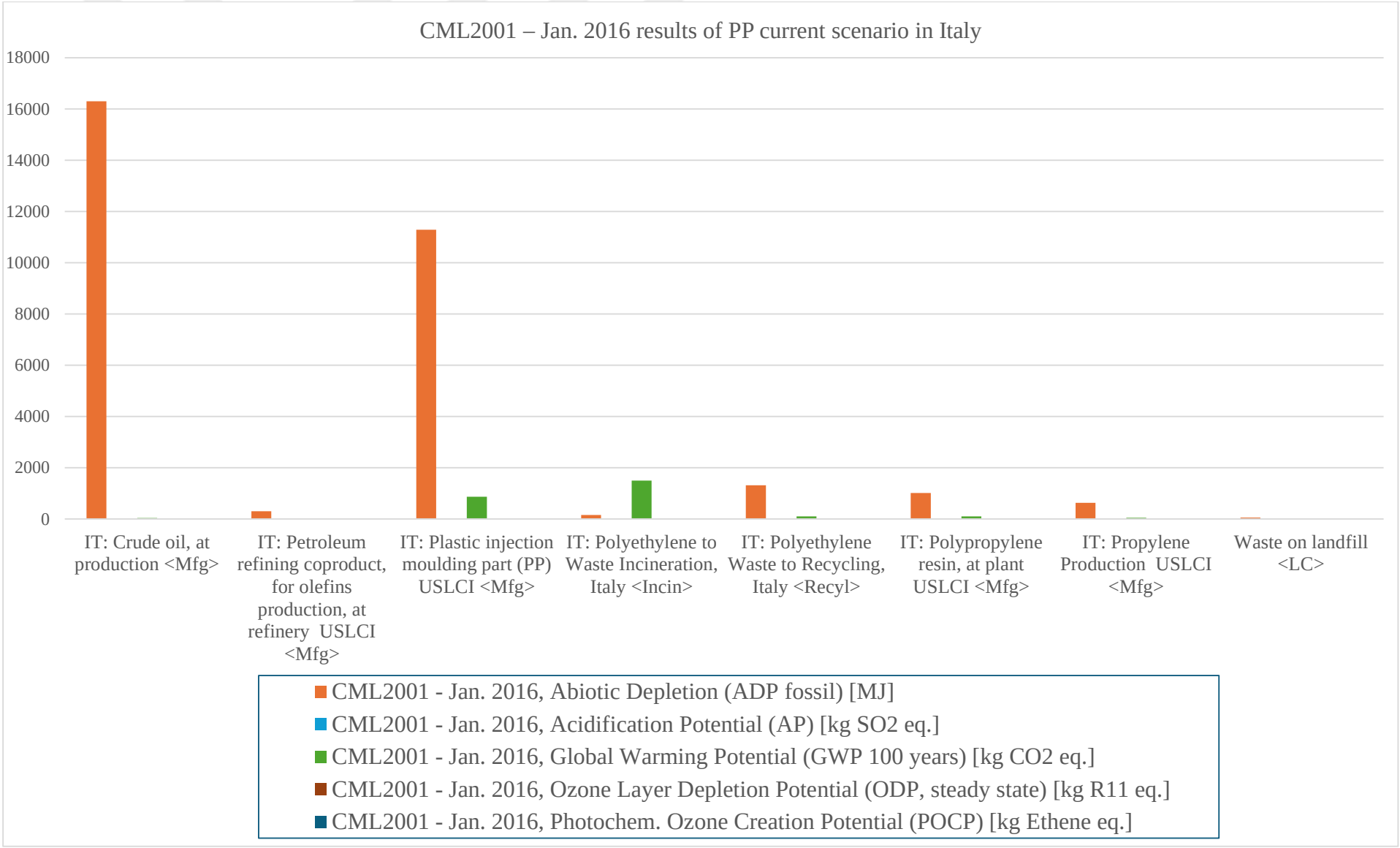

Figure 4.12. CML2001 – Jan. 2016 results of PP current scenario in Italy, with processes comprised.

4.1.3. Normalization

Normalization is a step that can provide results with common reference in LCIA methodologies, ReCiPe 2016 v1.1 and CML 2001 – Jan.2016 Characterization impact scores turn into a common referenced scores without unit for each LCIA methodology. With this optional step in impact assessment, one can make comparison among the impact categories of a chosen LCIA methodology (European Commission, 2010).

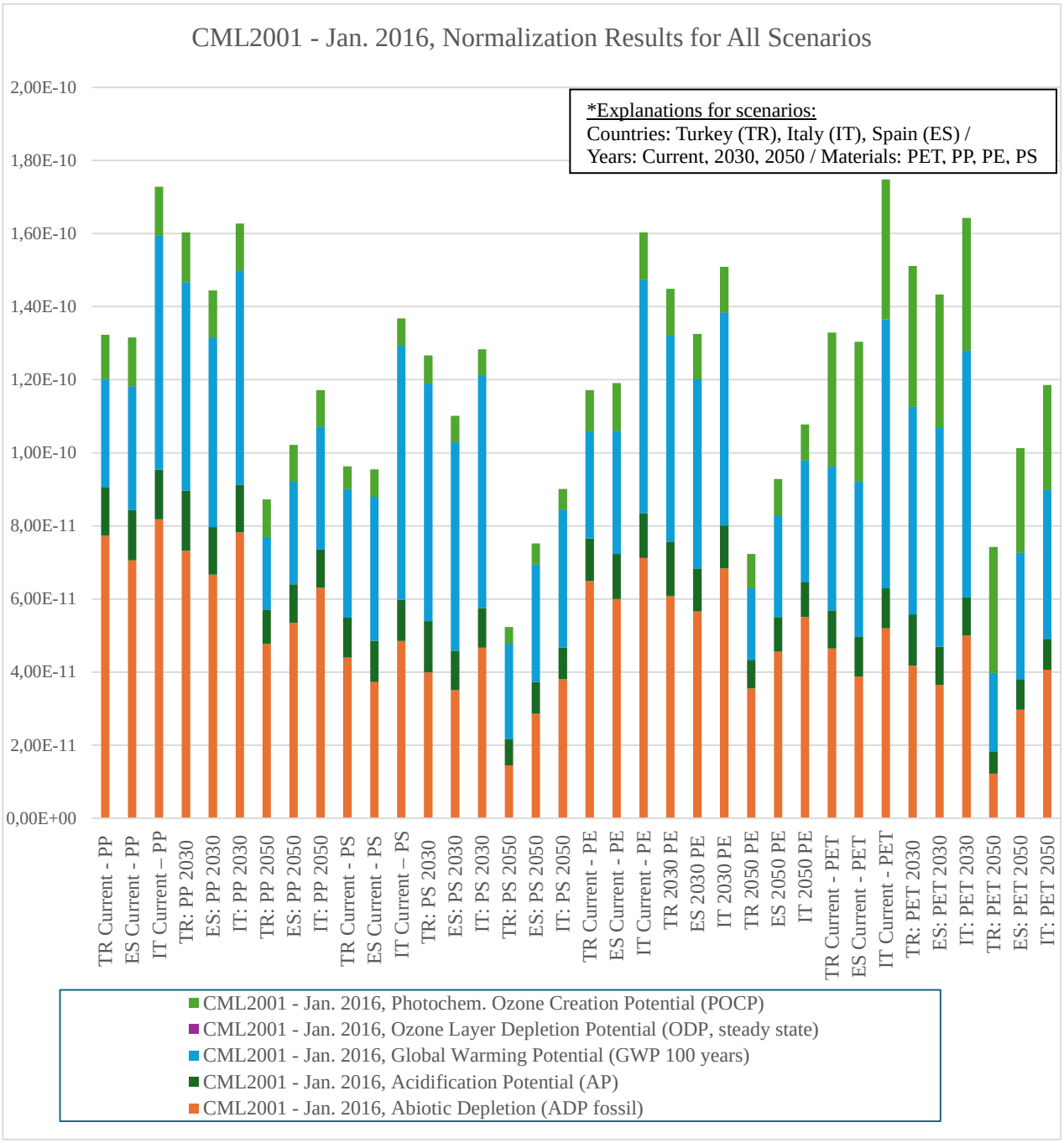

Figure 4.13. Comparison of CML normalization results, for all scenarios.

For the comparison of CML impact categories, CML2001 – Jan.2016, World, year 2000, incl biogenic carbon (global equivalents) normalization preference on GaBi 9.2.1 software was chosen. The normalization results of CML 2001 – Jan.2016 for impact categories of abiotic depletion (for fossil and elements), acidification potential, global warming potential, ozone layer depletion potential and photochemical ozone creation potential can be seen on the Figure 4.13. With these results, abiotic depletion (ADP fossil) impact category has become an important in the share of total impact scores of all scenarios. The second impact category that has a major share on the total impact scenario score has been global warming potential (GWP 100 years) impact category. It can be also observed on the below figure of Figure 4.14, CML2001 – Jan.2016, Abiotic Depletion (ADP fossil) impact category has had the biggest impact on all scenarios of packaging materials, due to highly dependence processes of whole scenarios. CML2001 – Jan.2016, Global Warming Potential (GWP 100 years) impact category has been the second impact score related to electricity grid mix used in countries (as mentioned in Figure 2.15, Figure 2.16 and 2.17 for current scenarios; Figure 2.18, 2.19 and 2.20 for future scenarios of Turkey) with different shares of renewable resources that are not sufficient for an environmentally beneficial process.

For global warming potential normalization result, the impact category was contributed by 36.6% to total normalization single score 4.41×10^{-9}. For abiotic depletion normalization result, 41.1% contribution to total normalization score of 4.41×10^{-9} has appeared. Within these scores, 2050 scenarios have had a lower impact. For abiotic depletion (ADP fossil), total score of 2050 scenarios was contributing in 25.6%, while total current scenario score was contributed in 38.3%, to the total ADP fossil normalization score. The remaining share was belonging to the 2030 scenarios, which has a middle significance, in between current and 2050 scenario's impacts. For global warming potential, current scenarios were contributed by 34.3% to the GWP total normalization score of 1.61×10^{-9} and 2050 scenarios were contributed by 22% to GWP total normalization score. For GWP, a remaining share of 43.7% had belonged to 2030 scenarios and, 2030 impact on GWP was significantly higher than other years. When it is seen Figure 4.13, high PET normalization scores on GWP for 2030 is remarkable with blue color. Thus, contributions from 2030 have become reasonable. Moreover, PET's complex production scheme and input requirements for production compared to other packaging materials has made PET 2030 scenarios biggest contributor.

After normalization result of abiotic depletion (ADP fossil) and global warming potential (GWP 100 years), the categories were assigned as CML2001 - Jan. 2016, Photochemical. Ozone Creation Potential (POCP), CML2001 - Jan. 2016, Acidification Potential (AP), and CML2001 - Jan. 2016, Ozone Layer Depletion Potential (ODP, steady state); third, fourth and fifth

normalization results, respectively. These order of impact categories can be seen on Figure 4.14. For acidification potential (AP) in CML, PET current scenario of Italy was made the highest contribution in 4.6%. for photochemical ozone creation potential (POCP), highest contributing scenario was PET 2030 scenario in Turkey in 6.5% of total POCP normalization score of 6 x 10^{-10}. And for ozone layer depletion (ODP, steady state) in CML normalization result, obtained scores were highest for three different scenarios of current situation PP in all countries, each has been contributed by 5.64%.

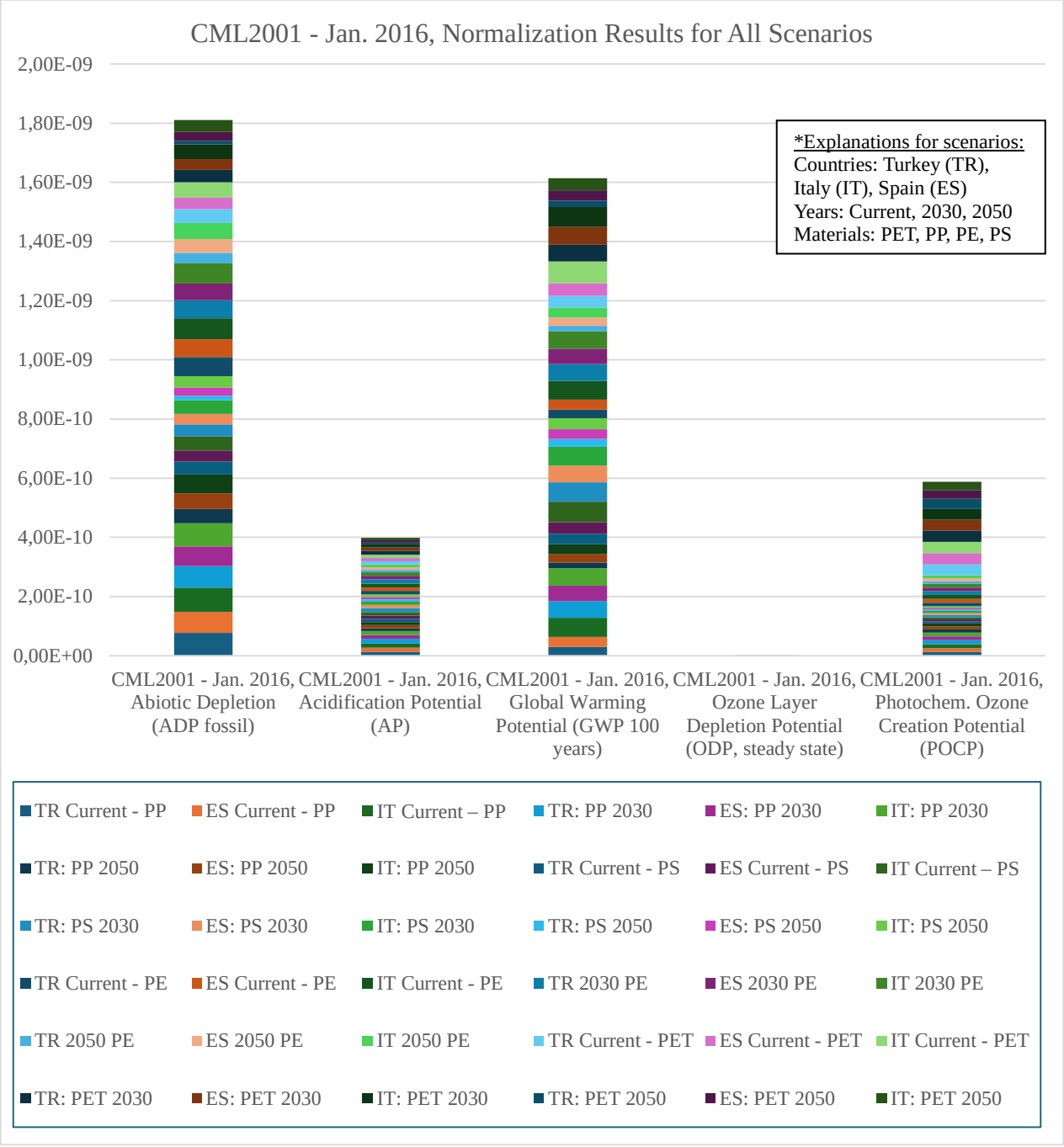

Figure 4.14. Comparison of CML impact categories, for all scenarios.

When two significant environmental impact category normalization scores of abiotic depletion and global warming potential in CML methodology were evaluated with respect to the contributions of each packaging material, the results were obtained the highest contribution to overall impact category normalization score in PP material for abiotic depletion and PET material for global warming potential. PP share in abiotic depletion normalization score in CML was highest with 33.8%, and PE material have followed this abiotic depletion normalization score with a second highest share of 28.6%. For PP and PE material, the life cycle inventory analysis (Table 3.3 and 3.4) was revealed that higher dependency on non-renewable resources was observed in these two packaging materials. High crude-oil and petroleum refining coproduct requirement in life cycles of PP and PE have led to high contribution shares in abiotic depletion normalization result. Ethylene and propylene have become monomers that can be polymerized to polyethylene (PE) and polypropylene (PP) materials with polymerization reactions, without adding that much high amounts of different chemicals to the production processes of their life cycles. PS has also been the lowest contributor to abiotic depletion normalization score with the share of 18.4%. When lower dependency on non-renewable resources of PS (Table 3.6) was considered, the result has become meaningful. For PET share in climate change normalization score in CML, 27.1% has been the highest contributor. This result of PET was followed by the normalization share of 26.4% for PS material in total climate change category normalization score. When two packaging materials of PS and PET were considered, more complex production processes, which are specific for these materials compared to PE and PP, have been observed in life cycle inventory analysis (Table 3.5 and 3.6). The complex production stages of ethylene oxide and paraxylene for PET and, benzene and ethylbenzene production for PS have consumed high amounts of electricity in their operations by regarding their life cycle inventory analysis. And, high electricity consumption amounts in such processes can be associated with high impact category scores of global warming or acidification. Electricity consumption in processes by contributing the related impact scores in high shares have led to higher environmental impact scores, when it was compared to less consumption of electricity with smaller contribution to the related impact category (Elduque et al., 2015). The lowest contributor for climate change in CML normalization score has belonged to PE material with 23.2% share. This result can be correlated with the lower electricity consumption compared to PET and PS materials. While it was depending more on the fossil-resource consumption with its less complex life cycle production stages which include crude-oil dependent monomer and polymer production, electricity consumption has been in less amount, too.

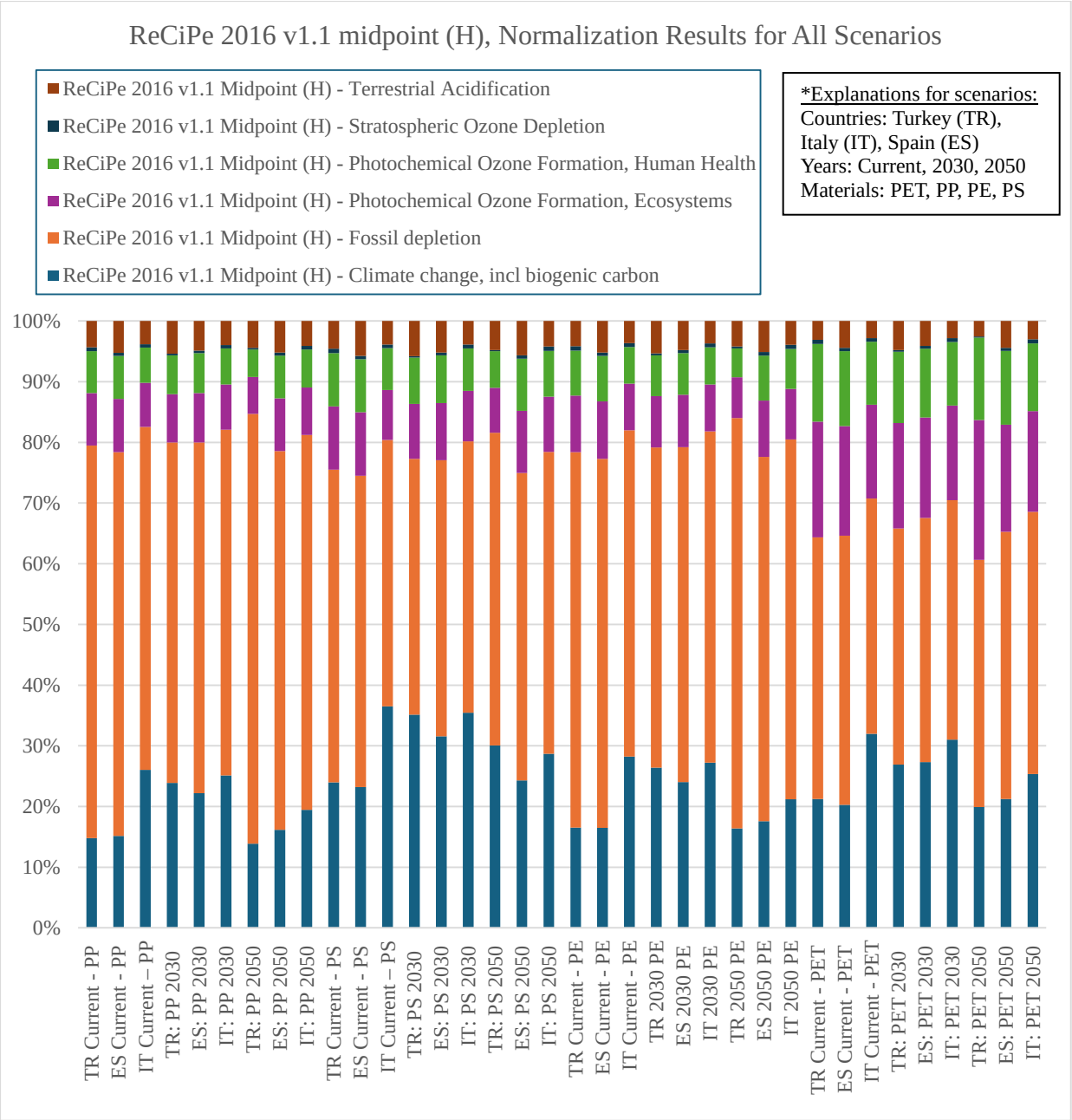

Figure 4.15. Comparison of ReCiPe 2016 midpoint (H) normalization results, for all scenarios.

To obtain ReCiPe 2016 v1.1 midpoint (H) normalization scores, ReCiPe 2016 v1.1 (H), Midpoint Normalization, World, incl biogenic carbon (person equivalents) preference in GaBi 9.1.2 software was chosen. On the Figure 4.15, the results of ReCiPe normalization can be seen. As it was seen on CML normalization results on Figure 4.13 and 4.14, fossil depletion and climate change environmental impact categories have had bigger shares on each scenario of packaging materials. Fossil depletion normalization score was contributed to single score of 35.7 by 52.1%. And, climate change category was contributed to overall ReCiPe climate change score by 24.2%. After these two high-scored results, as it was revealed in CML normalization, photochemical ozone formation terrestrial acidification and stratospheric ozone depletion categories were ranked, respectively.

Effect of 2050 scenarios on ReCiPe normalization scores was similar to CML. The results of 2050 scenarios have been contributed to overall ReCiPe midpoint climate change score of 8.64 by 34.4% for current scenarios and by 22.1% for 2050 scenarios. Again, 2030 scenarios for GWP have been the highest contributor, while 2050 has become lowest with 22.1% For fossil depletion, total normalization score for all scenarios was obtained 18.59, while 2050 scenarios had 27.4% contribution, and current scenarios had the 36.84% contribution to the total score of 18.59. With a smallest difference, again, the current scenarios for fossil depletion impact category have been the highest contributor. Midpoint (H) ReCiPe impact categories of fossil depletion and climate change through their high share on total impact score have shown the significance of dependency on fossil resources, electricity grid mix and share of renewable energy sources on the generation of electricity, which are consistent with the normalization results of CML methodology.

For the ReCiPe normalization scores of fossil depletion and climate change midpoint (H) impact categories, the highest contributor packaging materials were PP and PET respectively, which are again consistent with the CML normalization results. For PP packaging material, higher dependency on fossil resources compared to other packaging materials has led to the high amount of contribution in 32.6% to the fossil depletion ReCiPe normalization score. This share of 32.6% was followed by PE packaging material which contributes to ReCiPe fossil depletion normalization score in 28.1%. PE packaging material has had second highest dependency on non-renewable resources, when it was investigated life cycle inventory analysis. PS packaging material was indicated with its lowest contributing score in ReCiPe fossil depletion normalization result, with its lowest-dependency on fossil-resources, as it was discussed in CML normalization scores. Contribution of PS material to the fossil depletion category normalization score was 19.1%, which is very similar and consistent with CML abiotic depletion normalization result, repeatedly. For PET packaging material, ReCiPe normalization score of climate change environmental impact category has had the highest contribution in 27.1%, compared to other packaging materials. Then, second highest contribution to ReCiPe climate change normalization score was observed in PS packaging material, with the share of 26.3%. When these two packaging material were considered, their life cycles, which are consisted of high electricity consuming production processes of ethylene oxide, paraxylene for PET and ethylbenzene, benzene production for PS, have been observed by contributing such high results. High electricity consumption in a process of life cycle of a plastic have been associated with high contribution to the related environmental impact category. So, less consumption of electricity in a process can lead to lower impact category score result (Elduque et al., 2015). The lowest contributor of ReCiPe climate change normalization score was PE packaging

material with the share of 23.2%, which is exactly the same result in CML global warming potential normalization score.

4.1.4. Weighting

For weighting step, which is an optional step on LCIA according to ISO, preference of ReCiPe 2016 v1.1 (H/H), incl biogenic carbon (person equivalents weighted) was selected. The results obtained in weighting step have been not much differed from normalization results of ReCiPe 2016 Midpoint (H) and CML 2001-Jan.2016 results. Impact category of fossil depletion which belongs to "damage to resource scarcity" area of protection and, the other impact category of climate change, freshwater ecosystems which belongs to "damage to ecosystems" area of protection have highest total weighting scores in all scenarios as can be seen on Figure 4.16. Climate change, freshwater ecosystems was contributed to total weighting score by 19.17%. The other climate change endpoint impact categories for human health and terrestrial ecosystems were contributed to total impact score of 18023.95 by 14.37% and 19.16%. For fossil depletion endpoint impact category, weighting result has revealed a share of %29.72 in total weighting score. These were obtained similar results to midpoint and endpoint normalization for being first two major impact categories, but the ranking was change when different climate change impact categories are included in comparison. However, if it is analyzed one of climate change impact categories such as endpoint (H) climate change, freshwater ecosystems, its single contribution has become smaller when compared to fossil depletion.

For major environmental impact categories of fossil depletion and climate change, the results were similar to normalization results in ReCiPe and CML methodologies. In the fossil depletion endpoint (H) weighting score, the highest contribution has belonged to PP material in 37.9%, when it was compared to other packaging materials. Second highest contribution has belonged to PE material in 30.5%. The lowest contribution was associated with PET material which had a share of 15.6% in total fossil depletion weighting score. Lowest contributor result has been slightly differed from the normalization scores of resource depletion impact categories in CML and ReCiPe, which have the lowest contributor as PS material. However, this change is not a major change, and the ranking can be accepted nearly the same as CML and ReCiPe normalization scores. In the climate change endpoint (H) weighting scores in three different impact categories of human health, freshwater ecosystems and terrestrial ecosystems, the contribution of each impact category was the same. And, the highest contributor to these climate change weighting scores has been PET packaging material, while the lowest contributor has been the PE material. PET material was

contributed in 27.1% to total climate change weighting result, and this result was followed by PS material in 26.3%. Moreover, PE material was contributed in 23.2% to total climate change weighting result, as it was seen in CML and ReCiPe climate change normalization results.

When it comes to comparison of packaging materials, PP material has again had the highest share to the total weighting score with 27.6% share. Lowest score was obtained for PS material with share of 22.1%. For PE and PET materials which had the similar shares of 25.1% and 25.2% respectively. The polyolefin materials of PE and PET have had more dependency on fossil fuels. And, the weighting score of fossil depletion impact category has had a high share among the five impact categories. Furthermore, it can be seen on Figure 4.16 that weighting results of 2050 scenarios have had smaller share of 24%, 24.5%, 23.9% and 25% for PET, PE, PS and PP compared to current scenario shares. Climate change impact category which can be associated with non-renewable resource usage in electricity production such as combustion of fuel, coal or gas, has had significant effect on these year-based scenario results. Another effect can be related to reduction in packaging material in year-based scenarios (Table 3.1). So, the impact scores of environmental impact categories related to resource depletion have been obtained higher for the polyolefin group packaging materials, as can be seen on Figure 4.16.

For other weighting scores for endpoint (H) impact categories, ReCiPe 2016 v1.1 Endpoint (H) - Stratospheric Ozone Depletion had lowest contribution by 0.31% to total weighting score, ReCiPe 2016 v1.1 Endpoint (H) - Terrestrial Acidification had the second lowest contribution by 3.6%. Endpoint impact categories of Photochemical Ozone Formation for Ecosystems and for Human Health were contributed to total weighting score by 8.6% and 4.9%, respectively. Again, the results of weighting step were consistent with ranking in ReCiPe and CML normalization result.

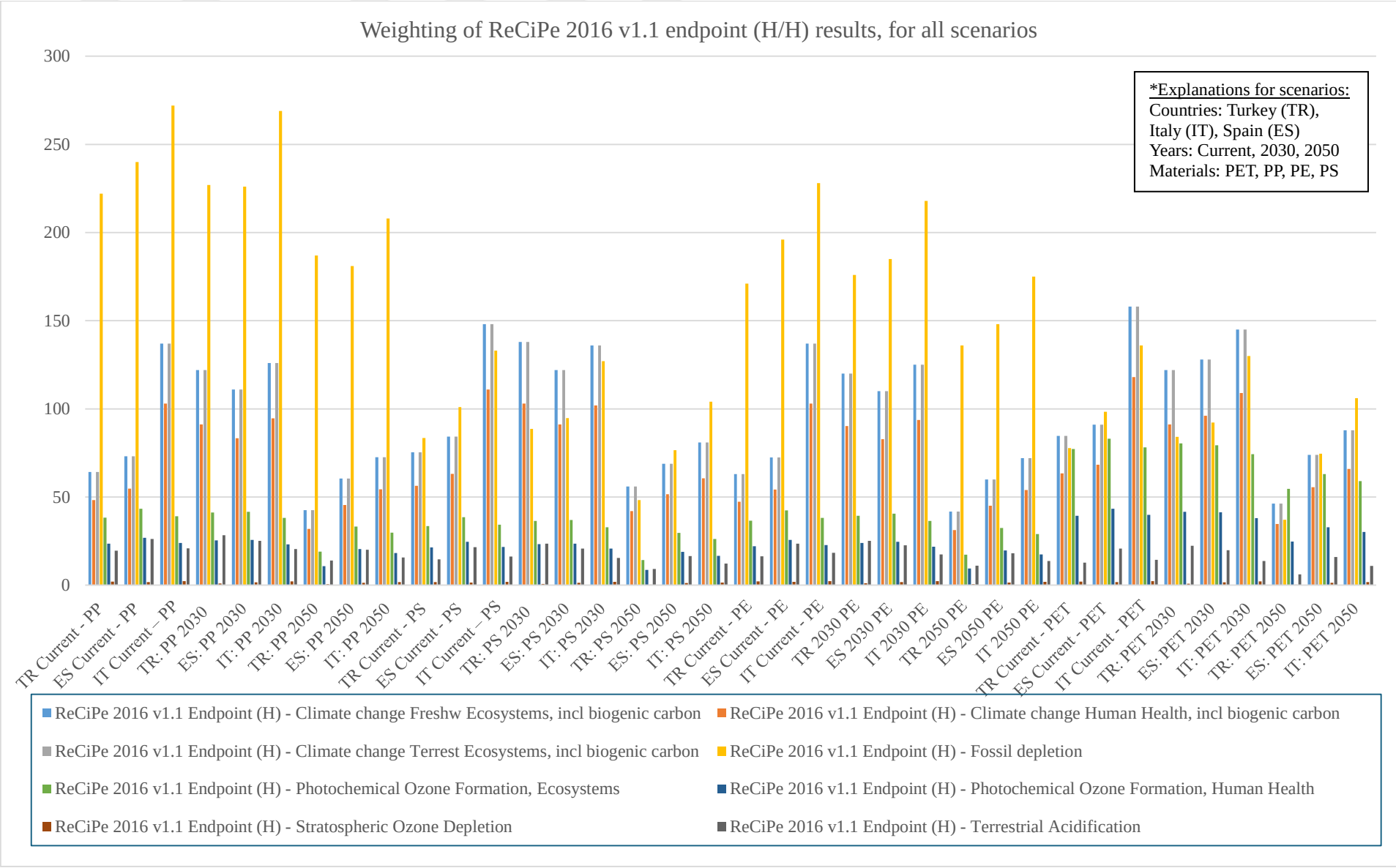

Figure 4.16. Weighting of ReCiPe 2016 v1.1 endpoint (H/H) results, for all scenarios.

5. CONCLUSIONS AND RECOMMENDATIONS

In this study, consumer goods plastic packaging materials of polyolefins, polystyrene, and polyethylene-terephthalate consumed in selected Mediterranean and coastal areas were studied by considering their potential environmental impacts via GaBi 9.2.1 software. These packaging materials were selected due to their high production in plastic applications and high disposal rates as they are known as single-use-plastics. Regarding the significant role of packaging plastics materials on production and consumption phases, environmental impact assessment has become continuously significant in the expressions of European Commission via Circular Economy Action Plan and Green Deal. Countries in Mediterranean region which are included in this study have been remarked by Mediterranean Action Plan which has also highlighted the plastic pollution caused by Mediterranean countries. For the scope of the study, the environmental damage which has been categorized as; resource depletion, climate change, acidification, ozone layer depletion and photochemical ozone formation.

Current and future scenarios regarding different recycling and recovery shares were specified for the plastic packaging materials. The results of scenarios for plastic packaging materials in different countries were obtained in different LCIA methodologies of CML2001 – Jan.2016 and ReCiPe 2016 v1.1. With these two different methodologies, different environmental impact categories with different units in midpoint, and endpoint were investigated. Normalization and weighting steps which give unitless results that can be compared, were also studied for life cycle impact assessment. Different electricity grid mixes were defined for the study, while future scenarios of Turkey were utilized from Turkey National Energy Plan prepared by Türkiye Ministry of Energy and Natural Resources. Share of resources in electricity power generation was determined for the year of 2030, not for 2050, by National Energy Plan. Thus, the 2050 electricity grid mix was prepared by estimating the distribution of renewable energy resources with respect to the information on National Energy Plan. The European future scenarios was studied by implementing another alternative of reduction in packaging material, according to the target. The target for European counties was set for 5% for 2030, and 10% for 2040, respectively. So, for 2050 a gradually increased target percent was established as 25%.

The environmental impacts on LCA study were conducted by including production processes of crude oil from resources which is required for each plastic material, production processes of plastic packaging materials, injection molding of plastic compound which prepares granulate or

compound for consumer, and end-of-life options such as recycling, energy recovery / incineration and landfill. For amount of electricity consumption in all the processes of plastic packaging material, database of GaBi software was utilized and adapted with different electricity grids of each selected country.

For each plastic packaging material, it has also seemed different impact categories were highlighted by LCA results. The packaging materials of PE and PP which belong to polyolefin material group and depend more on non-renewable crude oil resources have had highest environmental impact scores on fossil depletion, while PS and PET that have more complex production processes have had high impact scores on climate change environmental impact categories, due to heavy consumption of electricity in these processes. PP has had the shares in fossil depletion category for normalizations in ReCiPe by 32.26% and in CML methodologies by 33.8%. Moreover, fossil depletion weighting result in ReCiPe methodology for PP has had a share of 37.9%. And, for the other environmental impact categories of acidification potential, ozone layer depletion and photochemical ozone formation the impact results have had lower shares in total due to high importance of the climate change and fossil depletion environmental impact categories compared to other impact categories.

Year-based scenarios were also examined in the study, by performing current scenario with 2022 data, 2030 and 2050 scenarios with future improvements. For current scenarios, impact categories with highest shares have contributed to environmental impact results significantly. Current scenarios of all packaging materials have had a significant environmental impact rate of 36.84% in total normalization result of ReCiPe midpoint (H) fossil depletion, considering the other scenarios for the years of 2030 and 2050. And for 2050 scenarios, ReCiPe midpoint (H) normalization result has had a share of 27.4% for fossil depletion impact category, which has a lower impact among the other year-based scenarios. For climate change impact category, ReCiPe midpoint (H) normalization result has had 34.4% share for current scenarios, among other year-based scenarios. For the 2050 scenarios, the share of ReCiPe climate change normalization score result was 22.1% in total ReCiPe climate change normalization score of 8.64. For CML methodology, normalization results were similar to ones observed in ReCiPe midpoint normalization scores. When it was observed current total normalization of 1.61×10^{-9} for CML2001 – Jan. 2016 global warming potential impact category, normalization score share of 2050 scenarios was 22% in total CML GWP score of 1.61×10^{-9}. This result of 22% was same with ReCiPe climate change normalization score in 2050 scenarios. For the normalization score of current scenarios, the rate has resulted as 34.3% which indicates repeatedly the same result with ReCiPe climate change

midpoint normalization rate for current scenarios. For CML2001 – Jan. 2016 abiotic depletion category, result of normalization share for current scenarios has differed in a very small amount. The total result of current scenarios for abiotic depletion normalization was 6.93 x x 10^{-10} and the share of the current normalization result was 38.3% within total score of 1.81 x 10^{-9}. Share of 2050 normalization result was 25.6%. CML2001 – Jan. 2016 global warming potential impact category has had a share of 36.6% in the total CML normalization result of 4.41 x 10-9, while ReCipe climate change midpoint (H) impact category has had a share of 24.2% in the total ReCiPe normalization result of 35.7. For resource depletion impact categories of abiotic depletion in CML, and fossil depletion in ReCiPe, the shares of these impact categories have been different. CML abiotic depletion normalization share in total CML normalization result was 41.1%, while ReCiPe midpoint fossil depletion normalization share in total ReCiPe normalization result was 52.1%. For other impact categories, the order of normalization results was same in ReCiPe and CML methodologies. For example, normalization score of ozone layer depletion potential impact category in CML and normalization score of stratospheric ozone depletion in ReCiPe have had the lowest share of 0.522% for CML and 0.0000893% for ReCiPe, respectively.

To sum up, environmental impact categories of resource depletion and climate change have been important for life cycles of consumer goods plastic packaging. These two categories have had the highest share in normalization results of all scenarios, while other impact categories of photochemical ozone formation, acidification potential and ozone depletion potential were in lower ranks, as they were mentioned previously. By implementing the future improvements of future electricity grid mix based on more renewable energy resources, and packaging reduction target which leads lower consumption of resources, the environmental impact categories have had lower impact scores compared to current situations. For 2030 scenarios of Turkey, the electricity grid mix which was prepared according to the Turkey National Energy Plan has had increased share of renewable energy. The renewable energy in 2030 electricity generation was increased 25% compared to current electricity grid of Turkey prepared with TEİAŞ dataset. In 2050, electricity grid mix used in scenarios of Turkey, renewable energy share in electricity generation was increased by 128% compared to current electricity grid of Turkey. The reduction in packaging amount was 5% for 2030 Italy and Spain scenario and 25% for 2050 Italy and Spain scenario, respectively.

For weighting results, the trend, which is observed in year-based scenarios on higher-scored environmental impact categories of resource depletion and climate change, was observed similar to the trends in normalization scores, too. CML normalization result of GWP has differed this trend in a minor way, since the results were higher for 2030 scenario in weighting results. This can be

correlated to additional incineration shares on the end-of-life options in life cycles of packaging materials. Moreover, weighting results were performed via ReCiPe 2016 v1.1 (H/H), incl biogenic carbon (person equivalents weighted) option. Results of ReCiPe and CML can be differed, as it was seen on above. Processes of incineration added as an end-of-life option for future life cycles, olefin production, and plastic injection molding in all the life cycles of packaging materials were caused the environmental impact category results to increase in CML and ReCiPe methodology. So, the study of these packaging materials in three Mediterranean countries has implied the main impact category among the chosen impact categories. Resource depletion and climate change categories have become the most significant categories for environmental harm.

Furthermore, end-of-life scenarios in which includes different shares of incineration, recycling and landfill operations, have also become one of the elements that have impact on the results. It was observed that the scenarios with higher share of recycling and lower share of incineration/energy recovery has led to lower environmental impact scores due to incineration process and its CO_2 emissions. When the year-based scenarios were examined, 2050 scenarios which includes lower shares of incineration/energy recovery processes has reached lower environmental impact scores in overall comparison of year-based scenarios. After the results in CML normalization observed, scenarios of 2050 has had a lowest share of 24.7% in total CML normalization score, while 2030 scenarios has had the share of highest with 39.1%. 2030 scenarios were slightly higher than current year-based scenarios which have the share of 36.2% in total normalization score of CML. For ReCiPe midpoint normalization results among the year-based scenarios, the highest share of 38.2% has belonged to 2030 scenarios in total ReCiPe midpoint normalization score. For ReCiPe endpoint weighting scores, among the year-based scenarios 2030 scenarios was the highest one with %40.1, repeatedly. The impact of higher incineration rate in end-of-life stage of the scenarios and contribution of less implementation compared 2050 scenarios, have led to these results for 2030. When recycling and implementations which are related to electricity grids with higher renewable energy and packaging amount reduction, have changed the environmental impact scores that leads less harmful scores.

It was also concluded in this study that PP and PE plastic packaging materials have been recommended to be produced and consumed in less amounts when environmental impact category of resource depletion is considered. Their production and usage should be diminished in order to reduce environmental impact scores of resource depletion category of fossil depletion in CML 2001 – Jan.2016 and ReCiPe 2016 v1.1 methodologies. Fossil depletion environmental impact category has become the highest contributed impact category score to the overall normalization score among

other impact categories of climate change, photochemical ozone formation, acidification and stratospheric ozone depletion through the CML and ReCiPe methodologies. These two plastic packaging materials have had higher dependency on non-renewable resources compared to PS and PET packaging materials and their impact on resource depletion environmental impact categories were high. Fossil resource dependency of life cycles of PE and PP materials on the processes of ethylene production and propylene production respectively, have confirmed the highest score of fossil depletion impact category. Ethylene and propylene production processes are directly correlated to crude oil and petrochemical refining coproduct of naphtha and, these packaging materials life cycle have not consisted of any other chemical production processes according to life cycle inventory analysis. Contribution of PP and PE materials have had the normalization shares of 33.8% and 28.6% in CML and 32.6% and 28.1% in ReCiPe. As it was seen on the results, especially packaging material of PP in both methodologies has had highest share to the resource depletion normalization impact scores.

Life cycle processes of PET and PS materials have also had dependency on other chemical production processes of ethylene oxide and paraxylene for PET and benzene, ethylbenzene for PS, compared to PE and PP materials. So, the contributions of PS and PET to the resource depletion environmental impact categories in CML and ReCiPe were smaller and, their shares were 18.4% and 19.2% in CML and 19.1% and 20.3% in ReCiPe, respectively. PS material with its lowest share to the resource depletion normalization score can be emphasized. Since the packaging materials assessed in this study are highly used in packaging plastic market as single-use plastics (SUP), these crude-oil higher dependent packaging materials of PE and PP have been recommended to be used and produced less frequently, and PS material can be switched with two packaging materials of PE and PP, especially with PP material by outperforming the other packaging materials if environmental benefit of resource depletion impact category is considered.

If climate change impact category is considered, less usage and production of PET and PS plastic packaging materials are recommended in this study. Climate change environmental impact categories in CML and ReCiPe methodologies has resulted second among the other normalization scores of environmental impact categories performed. For the climate change impact category, PET and PS materials with their higher complex production processes are contributed higher amount compared to PE and PP materials. Their production stages have been different from PE and PP and been consisted of additional benzene and ethylbenzene production processes for PS and ethylene oxide and paraxylene production processes for PET, when life cycle inventory analysis was observed. These processes of production in life cycles of PET and PS have been associated with

high electricity consumption, and then they have led to higher contribution to the related environmental impact category result of climate change, compared to less electricity consuming processes in plastic material's life cycle. Contributions of PS and PET to the climate change environmental impact normalization results in CML and ReCiPe methodologies were higher compared to PE and PP, and shares of PS and PET in overall normalization score were 26.4% and 27.1% respectively in CML, and 26.3% and 27.1% respectively in ReCiPe. The lowest contribution to the normalization results of climate change environmental impact categories in CML and ReCiPe has belonged to PE material with share of 23.2% which is same share for both of the methodologies. The lowest contribution has resulted in PE packaging material which can be correlated with lower electricity consuming processes and higher crude-oil dependence on its life cycle. PE outperforms the other packaging materials of PP, PET and PS, when climate change environmental impact categories in CML and ReCiPe methodologies are considered. Especially, PET packaging material which is the highest contributor to the climate change impact category scores, should be switched with PE, if environmentally beneficial scores in climate change category will be favored.

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