

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

**LIFE CYCLE ASSESSMENT OF ELECTRIC VEHICLES AND INTERNAL
COMBUSTION ENGINE VEHICLES: FUTURE PROSPECTS**



M.Sc. THESIS

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Department of Environmental Engineering

Environmental Sciences Engineering and Management Programme

JANUARY 2025

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DÖNGÜ DEĞERLENDİRMESİ: GELECEK BEKLENTİLER**

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To my family,



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ABBREVIATIONS

ADP	: Abiotic Depletion Potential
AoPs	: Areas of Protection
AP	: Acidification Potential
BEV	: Battery Electric Vehicle
BRICS	: Brazil, Russia, India, China, and South Africa
CCaLC	: Carbon Calculations over the Life Cycle of Industrial Activities
CF	: Carbon Footprint
CH	: Switzerland
CML	: Institute of Environmental Sciences
CN	: Canada
DE	: Germany
EEA	: European Environment Agency
EP	: Eutrophication Potential
EU	: European Union
EV	: Electric Vehicle
FAETP	: Freshwater Aquatic Ecotoxicity
FCEV	: Fuel Cell Electric Vehicle
FPMF	: Fine Particulate Matter Formation
FR	: France
GHG	: Greenhouse Gas
GWP	: Global Warming Potential
HEV	: Hybrid Electric Vehicle
HTP	: Human Toxicity Potential
ICEV	: Internal Combustion Engine Vehicle
IEA	: International Energy Agency
ISO	: International Organization for Standardization
LCA	: Life Cycle Assessment
LCCA	: Life Cycle Cost Analysis
LCEA	: Life Cycle Energy Analysis
LCI	: Life Cycle Interpretation

LCI	: Life Cycle Inventory
LCIA	: Life Cycle Impact Assessment
LPG	: Liquefied Petroleum Gas
MAETP	: Marine Aquatic Ecotoxicity
OEF	: Organizational Environmental Footprint
OLDP	: Ozone Layer Depletion Potential
PEF	: Product Environmental Footprint
PHEV	: Plug-in Hybrid Electric Vehicle
PSP	: Photochemical Smog Potential
PV	: Photovoltaic
RD	: Resource Depletion
RPMs	: Revolutions Per Minute
SAM	: Social Accounting Matrix
SDGs	: Sustainable Development Goals
TETP	: Terrestrial Ecotoxicity
TOGG	: Türkiye's Automobile Joint Venture Group
UCTE	: United Center for Electricity
UN	: United Nations
US	: United States
USA	: United States of America
VOC	: Volatile Organic Compounds
WtE	: Waste-to-Energy

SYMBOLS

CFC	: Chlorofluorocarbon
CH₄	: Methane
CO	: Carbon Monoxide
CO₂	: Carbon Dioxide
DB	: Dichlorobenzene
HFCs	: Hydrofluorocarbons
km	: Kilometer
kWh	: Kilowatt-Hour
N₂O	: Nitrous Oxide
NO_x	: Nitrogen Oxide
PM	: Particulate Matter
SO₂	: Sulphur Dioxide



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LIFE CYCLE ASSESSMENT OF ELECTRIC VEHICLES AND INTERNAL COMBUSTION ENGINE VEHICLES: FUTURE PROSPECTS

SUMMARY

The transportation sector is a major contributor to global greenhouse gas emissions, accounting for around 20% of primary energy consumption and 23% of CO₂ emissions, with road transport playing a critical role in air pollution, particularly in the European Union. As the world increasingly turns its attention to climate change, electric vehicles (EVs) are emerging as a potentially cleaner alternative to internal combustion engine vehicles (ICEVs). However, despite the growing popularity of EVs, emissions from the transport sector have remained largely unchanged since 2005. In Türkiye, the adoption of EVs has experienced a surge, with the number of electric vehicles increasing from zero in 2012 to 81,900 in 2023. However, the environmental benefits of EVs heavily depend on the electricity used to charge them. As Türkiye continues to integrate renewable energy sources into its grid, the environmental footprint of EVs is expected to decrease. This shift, however, must be carefully tracked to guide future policies and decisions.

This thesis addresses the gap in evaluating the long-term environmental impacts of EVs compared to ICEVs, specifically focusing on Türkiye's changing electricity generation mix from 2020 to 2050. The study will conduct a detailed Life Cycle Assessment (LCA) of both EVs and ICEVs, assessing key environmental factors such as global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), ozone layer depletion potential (OLDP), photochemical smog potential (PSP) and human toxicity potential (HTP). The research aims to provide insights into the future sustainability of EV adoption in Türkiye and offer valuable data for policymakers, researchers, and industry stakeholders. The LCA will be performed using the CCaLC tool, which allows for a comprehensive analysis of each vehicle's environmental impact throughout its life cycle.

Türkiye's electricity generation mix has evolved significantly since 1990. In the 2000s, natural gas became the dominant energy source, while coal and hydropower continued to play substantial roles. However, renewable energy sources, including wind, solar, and geothermal, have rapidly expanded due to favorable policies and falling technology costs. This shift to renewables is essential for reducing the environmental impact of EVs, as a cleaner electricity grid will enhance the benefits of EV adoption. Although EVs have zero tailpipe emissions and offer high energy efficiency, challenges such as indirect emissions during production and emissions from electricity used to affect air quality and human health. Despite these challenges, EVs offer significant promise for reducing greenhouse gas emissions, particularly when powered by renewable or low-carbon electricity.

LCA is a valuable tool for understanding the full environmental impact of products by examining all stages, from raw material extraction to disposal. LCA has been

instrumental in reshaping public perception of various products, such as biofuels, which were initially considered green but later found to have significant environmental drawbacks. The LCA methodology follows four key stages: goal and scope definition, inventory analysis, impact assessment, and interpretation. For this study, the goal is to assess the environmental impact of EVs and ICEVs in Türkiye, considering the full life cycle, including raw material extraction, production, use, and disposal. System boundaries are defined using the cradle-to-grave approach, ensuring that all relevant processes are included, while negligible ones are excluded.

The initial findings indicate that the production phase of EVs generates a higher environmental impact compared to other stages of the life cycle, particularly due to the energy-intensive nature of battery manufacturing. However, in the use phase, EVs are expected to outperform ICEVs as Türkiye's electricity grid becomes cleaner. For both vehicle types, the largest environmental impact stems from raw material supply, particularly the production of tires and fuel. The usage phase, driven by energy consumption, is also a significant contributor. International studies have shown that the life cycle impacts of EVs improve over time as renewable energy sources increase, especially in countries with cleaner grids.

This study developed a life cycle inventory based on a "cradle-to-grave" approach, encompassing raw material production, vehicle manufacturing and assembly, transportation, usage, and disposal phases. The functional unit is expressed in terms of the distance traveled per kilometer over the vehicle's lifespan. Assumptions for the LCA model include a sedan vehicle type, with a 20-year lifespan and 400,000 km for ICEVs, and a 15-year lifespan and 300,000 km for EVs. Both vehicle types are assumed to be driven 20,000 km annually. ICEVs consume 5.6 liters of fuel per 100 km, while EVs use 10 kWh per 100 km, and a 7% recycling rate is assumed based on Türkiye's average. The study utilizes the CML 2001 methodology to assess environmental impacts, focusing on six categories.

The analysis across six impact categories reveals notable differences between EVs and ICEVs. In 2020, EVs emitted approximately 40,000 kg CO₂ eq, compared to 90,000 kg CO₂ eq for ICEVs, showing a substantial reduction in carbon emissions for EVs. Over time, both vehicle types see a reduction in GWP, with EVs benefiting more as renewable energy integration grows. Regarding AP, EVs showed a slightly higher value than ICEVs in 2020 but are expected to improve by 2050 as cleaner production methods and renewable energy use increase. For EP, EVs have a significant advantage, with values ranging from 70 to 90 kg PO₄ eq, while ICEVs maintained a steady 25 kg PO₄ eq, indicating EVs' superior potential in reducing nutrient pollution. Although the OLDP was similar for both vehicle types, EVs showed a slight edge, with a marginal decline in ozone-depleting substances during their use phase. For PSP, EVs exhibited a notable reduction, particularly during the use phase, while ICEVs contributed more to smog due to raw material extraction. Finally, while EVs demonstrated a gradual reduction in human toxicity potential, they still had a higher toxicity potential compared to ICEVs, mainly due to the environmental impact of battery production and the need for improved battery recycling.

Expert opinion was gathered through a survey of 54 participants, who were asked to assign weights to six environmental impact categories. The results were used to create a unified score for each vehicle type, offering a balanced evaluation of their

environmental effects. The survey revealed that 28% of participants did not own a vehicle, while 72% were vehicle owners, with 64% owning ICEVs, 6% owning HEVs, and 2% owning EVs. GWP received the highest priority, with 67% of respondents, while AP, EP, and OLDP received fewer votes across various weight categories. The assigned weights were as follows: GWP (0.25), AP (0.16), EP (0.09), OLDP (0.17), PSP (0.16), and HTP (0.17), reflecting the varying importance given to each impact category.

In 2020, the overall normalized impact of ICEVs was 20% higher than that of EVs, and this difference increased to 28% by 2050 according to the survey results. This suggests that when impacts are weighted based on survey responses, EVs become a more environmentally friendly alternative over time. When equal impact weights were applied, the difference in overall normalized impact between EVs and ICEVs was 8.7% in 2020, increasing to 17.7% by 2050. However, in this case, the overall difference was less pronounced, underscoring the importance of considering weighted environmental impacts for a more accurate sustainability assessment of both vehicle types.

The study also included a sensitivity analysis, examining the effects of longer vehicle lifetimes and tire usage on the environmental performance of both vehicle types. It was found that energy consumption during the use phase had the largest environmental impact for both vehicle types. For EVs, energy consumption during use accounted for about 95% of the GWP change in the lifetime scenario, while for ICEVs, it was 35%. The reliance on non-renewable energy in 2020 had a more significant impact for EVs compared to 2050, when renewable energy is expected to play a larger role in electricity generation. Tire usage also contributed to the environmental impact, though its effect was smaller than that of energy consumption.

In conclusion, the study underscores the potential of EVs to significantly reduce environmental impacts, particularly in terms of carbon emissions and air quality. However, the findings also highlight the need for further improvements in battery production, recycling, and energy production source management to minimize the overall environmental impact. Integrating renewable energy into Türkiye's electricity grid will be a critical factor in enhancing the environmental benefits of EVs. The study provides key insights into the sustainability of EV adoption in Türkiye, offering valuable guidance for policymakers and industry stakeholders in the transition to a cleaner transportation sector.



ELEKTRİKLİ VE İÇTEN YANMALI MOTORLU ARAÇLARIN YAŞAM DÖNGÜ DEĞERLENDİRMESİ: GELECEK BEKLENTİLER

ÖZET

Ulaşım sektörü, küresel sera gazı emisyonlarına önemli bir katkı sağlamakta olup, toplam birincil enerji tüketiminin yaklaşık %20'sini ve CO₂ emisyonlarının %23'ünü oluşturmaktadır. Avrupa Birliği'nde, özellikle karayolu taşımacılığı, hava kirliliğinde büyük bir rol oynamaktadır. Elektrikli araçların (EA) artan popülaritesine rağmen, ulaşım sektöründeki emisyonlar 2005 yılından bu yana büyük ölçüde değişim göstermemiştir. Türkiye'de ise EA kullanımı hızla artmış, 2012'de sıfır olan EA sayısı 2023 yılı itibariyle 81.900'e ulaşmıştır. Ancak, EA'ların çevresel etkileri, büyük ölçüde bu araçların şarj edildiği elektriğin kaynağına bağlıdır. Türkiye'nin elektrik şebekesine yenilenebilir enerji kaynaklarının entegrasyonu arttıkça, EA'ların çevresel etkilerinin iyileşmesi de beklenmektedir. Bu geçişin yakından takip edilmesi ve uyumunun sağlanması, gelecekteki politikalar ve kararlar için önemli rol oynamaktadır.

Bu tez, EA'ların uzun vadeli çevresel etkilerinin, içten yanmalı motorlu araçlarla (İYMA) karşılaştırmalı olarak değerlendirilmesindeki eksikliği gidermeyi hedeflemekte ve özellikle Türkiye'nin 2020'den 2050'ye kadar değişen elektrik üretim dağılımını ele almaktadır. Hem EA hem de İYMA için kapsamlı bir yaşam döngüsü değerlendirmesi (YDD) gerçekleştirilmiştir ve çevresel etkiler, özellikle küresel ısınma potansiyeli, asidifikasyon potansiyeli, ötrofikasyon potansiyeli, ozon tabakasının incilmesi potansiyeli, fotokimyasal duman oluşum potansiyeli ve insan toksisitesi potansiyeli gibi kritik faktörler incelenmiştir. Bu araştırma, Türkiye'de EA adaptasyonunun gelecekteki sürdürülebilirliği hakkında önemli bilgiler sunmayı ve politika yapıcılar, araştırmacılar ve endüstri paydaşları için değerli veriler sağlamayı hedeflemektedir. YDD, her iki aracın çevresel etkilerini yaşam döngüsü boyunca kapsamlı bir şekilde analiz edebilen CCaLC aracıyla yapılmıştır.

Türkiye'nin elektrik üretim dağılımı, 1990'dan bu yana önemli ölçüde değişmiştir. 2000'li yıllarda doğal gaz, baskın enerji kaynağıyken kömür ve hidroelektrik de önemli rol oynamaya devam etmekteydi. Ancak son yıllarda, yenilenebilir enerji kaynaklarının kullanımı, özellikle rüzgar, güneş ve jeotermal, politika teşvikleri ve teknoloji maliyetlerindeki düşüşlerin etkisiyle hızlı bir şekilde yaygınlaşmıştır. Bu geçiş, EA'ların çevresel etkilerinin azaltılması için kritik bir faktör haline gelmektedir. EA'lar, minimum egzoz emisyonuna sahip olsalar da, üretim esnasındaki dolaylı emisyonlar ve kullanılan elektrikten kaynaklı emisyonlar insan sağlığını ve ekolojik dengeyi etkilemektedir. Buna rağmen, EA'lar, özellikle yenilenebilir veya yenilenebilir enerjiyle çalıştıklarında, sera gazı emisyonlarını azaltma anlamında büyük bir potansiyel sunmaktadır.

YDD, ürünlerin çevresel etkilerini incelemeye kullanılan, ham madde çıkarımından atığa kadar tüm aşamaların incelenbildiği ve günümüzde yaygın olarak kullanılan bir yöntemdir. YDD metodolojisi, dört temel aşamadan oluşur: hedef ve kapsam tanımlaması, envanter analizi, etki değerlendirmesi ve yorumlama. Bu tez çalışması için hedef, Türkiye'deki EA'lar ve İYMA'ların çevresel etkilerini tam yaşam döngüsü boyunca değerlendirmektir; bu, ham madde çıkarımı, üretim, kullanım ve bertaraf aşamalarını kapsamaktadır. Sistem sınırları, tüm ilgili süreçlerin dahil edilmesini sağlayan "beşikten mezara" yaklaşımına göre tanımlanmıştır.

İlk bulgular, elektrikli araçların üretim aşamasının, özellikle batarya üretiminin yoğun enerji ihtiyacı nedeniyle daha yüksek çevresel etkilere sahip olduğunu göstermektedir. Ancak, kullanım aşamasında, Türkiye'nin elektrik şebekesinin daha temiz hale gelmesiyle, EA'ların İYMA'lara göre daha düşük çevresel etkilere sahip olması beklenmektedir. Her iki araç türü için de en büyük çevresel etki, ham madde temini aşamasından kaynaklanmakta, özellikle değerli metal çıkarımı ve yakıt üretimi bu aşamada önemli bir rol oynamaktadır. Kullanım aşaması ise, enerji tüketimi nedeniyle çevresel etkiyi artıran bir faktördür. Uluslararası çalışmalar, EA'ların yaşam döngüsü etkilerinin, yenilenebilir enerji kaynaklarının artmasıyla zamanla iyileştiğini, özellikle daha temiz elektrik şebekelerine sahip ülkelerde bu etkinin belirgin olduğunu göstermektedir.

Bu çalışmada, "beşikten mezara" yaklaşımı kullanılarak bir yaşam döngüsü envanteri geliştirilmiştir; bu envanterler ham madde üretimi, araç üretimi ve montajı, taşıma, kullanım ve bertaraf aşamalarını kapsamaktadır. Fonksiyonel birim, aracın yaşam süresi boyunca kat ettiği mesafe, kilometre cinsinden ifade edilmiştir. YDD modelinin varsayımları arasında sedan tipindeki araçlar yer almakta olup, İYMA'ların ömrü 20 yıl ve 400.000 km, EA'ların ömrü ise 15 yıl ve 300.000 km olarak kabul edilmiştir. Her iki araç türünün yıllık kullanım mesafesi 20.000 km olarak varsayılmıştır. İYMA 100 km başına 5,6 litre yakıt tüketirken EA 100 km başına 10 kWh enerji tüketmektedir. Türkiye'nin ortalama geri dönüşüm oranı olan %7'de göz önünde bulundurulmuştur. Çalışma, çevresel etkileri değerlendirmek için CML 2001 metodolojisini kullanmakta olup, altı farklı etki kategorisi üzerinde yoğunlaşmaktadır.

Altı etki kategorisi için yapılan değerlendirme, EA ile İYMA arasında önemli farklar olduğunu ortaya koymaktadır. 2020 yılında, EA yaklaşık 40.000 kg CO₂ eşdeğeri salımı yaparken, İYMA 90.000 kg CO₂ eşdeğeri salımı yapmaktadır. Bu da EA'ların karbon emisyonlarında önemli bir azalma olduğunu göstermektedir. Zamanla, her iki araç türü de küresel ısınma potansiyelinde bir azalma yaşasa da, EA özellikle yenilenebilir enerji entegrasyonunun artmasıyla daha büyük bir azalma göstermektedir. Asidifikasyon potansiyeli açısından, EA 2020 yılında İYMA'lara göre biraz daha yüksek bir etkiye sahipken, 2050 yılına gelindiğinde daha temiz üretim yöntemleri ve yenilenebilir enerji kullanımıyla EA'ların etkisinin İYMA'lara göre daha fazla azalması beklenmektedir. Ötrafikasyon potansiyeli, EA'larda 70 ile 90 kg PO₄ eşdeğeri arasında değişirken, İYMA 25 kg PO₄ eşdeğeri ile sabit kalmaktadır. Ozon tabakasının incelleme potansiyeli açısından ise, her iki araç türü benzer etkilere sahip olmasına rağmen, EA kullanım aşamasında küçük bir azalma göstermektedir. Fotokimyasal duman oluşumu potansiyeli açısından ise, EA özellikle kullanım aşamasında önemli bir azalma sergilemekte, İYMA ise ham madde çıkarımı nedeniyle daha fazla duman oluşumuna neden olmaktadır. Son olarak, EA insan toksisitesi

potansiyelinde zamanla bir azalma göstermiş olsa da, batarya üretiminin çevresel etkisi nedeniyle hâlâ İYMA'lara göre daha yüksek bir toksisite potansiyeline sahiptirler.

Çalışmada, 54 katılımcıdan alınan uzman geri bildirimiyle altı çevresel etki kategorisi için ağırlıklar belirlenmiş ve bu ağırlıklar her araç türü için tek bir puan oluşturulmasında kullanılmıştır. Anket sonuçları, katılımcıların %28'inin araç sahibi olmadığını, %72'sinin ise araç sahibi olduğunu, araç sahiplerinin %64'ünün İYMA'ya, %6'sının hibrit EA'ya ve %2'sinin EA'ya sahip olduğunu göstermektedir. Küresel ısınma potansiyeli, %67 ile en yüksek önceliği alırken, asidifikasyon, ötrafikasyon ve ozon tabakasının incelmeye potansiyeli çeşitli ağırlık kategorilerinde daha az oy almıştır. Belirlenen ağırlıklar sırasıyla: Küresel ısınma potansiyeli (0,25), asidifikasyon potansiyeli (0,16), ötrafikasyon potansiyeli (0,09), ozon tabakasının incelmeye potansiyeli (0,17), fotokimyasal duman oluşumu potansiyeli (0,16) ve insan toksisitesi potansiyeli (0,17) olarak belirlenmiştir ve her etki kategorisinin farklı öncelikleri yansıttığı görülmektedir.

2020'de İYMA'ların çevresel etkisi, EA'lara göre %20 daha yüksekken, bu fark 2050'ye kadar %28'e kadar artmaktadır. Bu, anket sonuçlarına göre, EA'ların zamanla daha çevre dostu bir alternatif haline geldiğini göstermektedir. Ancak, aynı ağırlıklar eşit kabul edildiğinde ise, 2020'deki çevresel etkiler arasındaki fark %8,7, 2050'de ise %17,7 olarak hesaplanmıştır. Bu durumda, çevresel etkilerin eşit ağırlıklarla değerlendirilmesi, her iki araç türü arasındaki farkın daha az belirgin olduğunu ancak çevresel etkilerin ağırlıklı olarak değerlendirilmesinin daha doğru bir sürdürülebilirlik değerlendirmesi sağladığını göstermektedir.

Çalışma ayrıca, uzun araç ömrü ve tekerlek kullanımı gibi etmenlerin her iki araç türünün çevresel performansı üzerindeki etkilerini inceleyen bir duyarlılık analizini de içermektedir. Araç kullanım aşamasındaki enerji tüketiminin her iki araç türü için de çevresel etkilerin en büyük faktörü olduğu bulunmuştur. EA'lar için enerji tüketimi, yaşam süresinin uzatılması senaryosunda küresel ısınma potansiyeli değişiminin %95'ini oluştururken, İYMA'lar için bu oran %35'tir. 2020'deki yenilenebilir olmayan enerjiye bağımlılık, EA'lar için 2050'ye göre daha büyük bir etkiye sahiptir. Çünkü 2050'de yenilenebilir enerji daha önemli bir rol oynamaktadır. Tekerlek kullanımı da çevresel etkiye katkı sağlamakta ancak bunun etkisi enerji tüketiminden daha düşük kalmaktadır.

Sonuç olarak, bu çalışma, EA'ların özellikle karbon emisyonları ve hava kalitesi açısından çevresel etkileri önemli ölçüde azaltma potansiyeline sahip olduğunu vurgulamaktadır. Bununla birlikte, batarya üretimi, geri dönüşüm ve enerji üretim kaynaklarının yönetimi gibi alanlarda daha fazla yenilik ve geliştirme yapılması gerektiği de ortaya çıkmıştır. Türkiye'nin elektrik şebekesine yenilenebilir enerji entegrasyonu, EA'ların çevresel faydalarını artıracak önemli bir faktör olacaktır. Bu çalışma, Türkiye'de EA yaygınlığının sürdürülebilirliği hakkında önemli değerlendirmeler sağlamakta olup, politika yapıcılar ve endüstri paydaşları için değerli bir öngörü sunmaktadır.



1. INTRODUCTION

1.1 Significance of Thesis Topic

Almost all economic and social activities cause air pollution emissions. The transport sector is one of the most significant greenhouse gas (GHG) emissions producers in the European Union (EEA, 2024). Road transport is known to be a major source of atmospheric pollution (Hoofman, et al., 2016; EEA, 2024). Over the past few decades, the transport sector has made minimal progress in reducing these emissions. As global attempts to combat climate change and reduce the release of GHG, electric vehicles (EVs) have emerged as a possible alternative to traditional internal combustion engine vehicles (ICEVs). Although measures like the growing adoption of EVs have been implemented to address this issue, emissions have remained largely unchanged since 2005 (EEA, 2024). EV sales continue to grow and are expected to reach approximately 17 million in 2024, accounting for more than 20% of all vehicles sold globally (Global EV Outlook, 2024). While the growing adoption of EVs represents a significant step forward, it has yet to translate into substantial overall reductions in transport-related emissions across the European Union.

EVs are often perceived as a sustainable and environmentally friendly solution, but their environmental advantages are especially highly sensitive to the electricity generation mix. In Türkiye, where the share of renewable energy in electricity production is projected to increase over the next decades, the environmental profile of EVs is expected to improve significantly. However, this improvement must be quantified to guide stakeholders in making informed decisions.

This thesis addresses a critical gap in the literature by providing a forward-looking life cycle assessment (LCA) comparison of EVs and ICEVs under varying electricity generation scenarios in Türkiye. The inclusion of expert-driven weighting to aggregate impact factors adds methodological thoroughness and ensures that the analysis reflects multidisciplinary perspectives. Furthermore, the study's outcomes are anticipated to inform policymakers, industry stakeholders, and researchers about the environmental

trade-offs of transitioning to EVs and the importance of accelerating renewable energy adoption.

By aligning with global sustainability goals and focusing on Türkiye's specific energy context, this research advances the understanding of EVs' role in combating climate change while highlighting the challenges and opportunities associated with their widespread adoption.

1.2 Aim and Scope of Thesis

The aim of this thesis is to conduct a comprehensive LCA of EVs and ICEVs, considering Türkiye's evolving electricity generation mix from 2020 to 2050. The study will analyze and compare the environmental impacts of these vehicle types based on six key impact factors to identify future prospects for EV adoption in Türkiye by using the Carbon Calculations over the Life Cycle of Industrial Activities (CCaLC) tool. By evaluating different electricity generation mix scenarios, the study aims to provide valuable insights into the future prospects of EVs and their role in achieving sustainable transportation and policy-making. This study provides a comprehensive evaluation of the environmental impacts related with EVs and ICEVs throughout their entire life cycle, from raw material extraction to end-of-life disposal.

To enhance the interpretation of results, a weighting method will be applied to aggregate these impact factors into a single value, reflecting expert opinions from environmental engineering professionals.

The study's scope is to compare the environmental impacts of EVs and ICEVs with different electricity production mix in Türkiye during 2020-2050 with LCA. Six environmental impact factors of different scenarios which represent different each year were compared. The next sections describe the LCA model's boundaries, scope, and functional unit, as well as scenario definitions, underlying assumptions, and life cycle inventories for each scenario.

2. LITERATURE REVIEW

Advances in technology, rapid population expansion, and increased globalization have hastened the depletion of nonrenewable energy supplies, particularly fossil fuels such as petroleum. Global primary energy consumption increased by 2.2% in 2017, above the decade-long average annual growth rate of 1.7% (IEA, 2019). Fossil fuels remain the primary energy source globally, contributing to around 85% of energy consumption, especially in sectors like manufacturing, heating, transportation, and various other activities (IEA, 2019). Vehicles play a substantial role in this energy demand, as they rely on propulsion systems to operate. Transportation of goods and people is responsible for nearly 20% of primary energy usage, 23% of CO₂ emissions, and approximately 14% of global GHG emissions (IEA, 2019). These systems are primarily based on two technologies: internal combustion engines, which are the most prevalent, and EV (Özbay, et al., 2017). In this context, EVs have emerged as a promising alternative to traditional ICEVs, offering the potential to mitigate environmental impacts.

Although an EV produces no tailpipe emissions during operation, the electricity used to power it may have been generated from fossil fuels, adding to air pollution and carbon dioxide (CO₂) emissions (Pipitone et al., 2021). As a result, identifying the source or mix of sources used to generate power is an important component in assessing the environmental impact of EVs. If the electricity is exclusively obtained from renewable sources such as hydropower, solar, or wind energy, the operation of an EV produces minimum pollutant emissions (Pipitone, et al., 2021). However, electricity is not only produced from renewable sources and often comes from a mix of sources, including fossil fuels (e.g., coal, natural gas, oil) with associated carbon footprints (CF), or nuclear energy, which generates hazardous waste. Each country has a unique electricity generation mix, commonly referred to as its "electricity mix," which significantly influences the environmental implications of EV usage.

Energy generation is important to modern economies' sustainability and resilience (National Geographic, 2022). The energy mix, or the proportion of energy derived

from diverse sources such as fossil fuels, nuclear power, and renewables, is a dynamic measure influenced by resource availability, technical breakthroughs, environmental policies, and economic considerations. Non-renewable sources like coal, oil, and natural gas have historically dominated energy production due to their high energy density and established infrastructure (National Geographic, 2022). However, the increasing urgency to address climate change and decrease carbon emissions has driven a global shift toward renewable sources, such as wind, solar, and geothermal energy.

The electricity generation trends in Türkiye between 1990 and 2023 are illustrated in the Figure 2.1 (IEA, 2023). Natural gas emerged as the primary energy source from the early 2000s, reflecting investments in its infrastructure. Coal started to decrease in the early 2000s and increased again in the early 2015s and reached the same levels. Coal and hydroelectric power have also maintained significant contributions, though the latter exhibits fluctuations due to variable water availability. Renewable sources like wind, solar photovoltaic (PV), and geothermal have shown substantial growth in recent years, underpinned by supportive policies and declining technology costs. Despite these advances, the overall energy mix still relies heavily on fossil fuels, underscoring the challenges of transitioning to a more sustainable energy grid. This evolution highlights the interplay between policy, market forces, and environmental priorities in shaping the energy landscape.

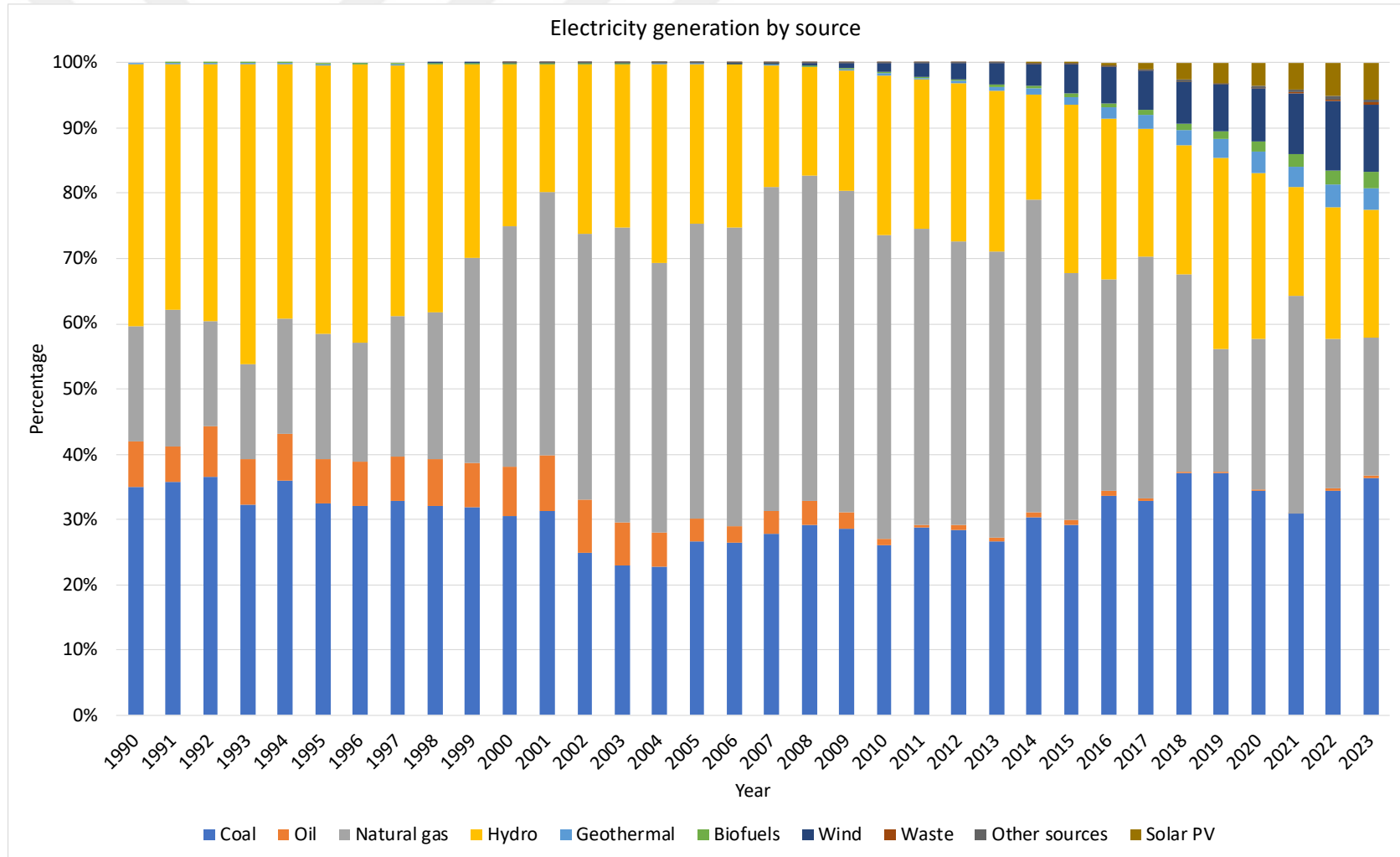


Figure 2.1: Electricity generation in Türkiye by source in 1990-2023 (IEA, 2023).

2.1 Historical Development of Vehicles

ICEV, fuelled by fossil fuels like gasoline or diesel, have been the dominant mode of transportation for over a century. These vehicles rely on the combustion of fuel in an engine to produce mechanical energy, which powers the vehicle. While ICEVs are well-known for their mature technology, extensive infrastructure, and affordability, their environmental drawbacks, including high CO₂ emissions and air pollution, have spurred the search for cleaner alternatives (Tören & Mollahasanoglu, 2022).

ICEVs can be classified into two categories according to fuel type Figure 2.2 (Xia & Li, 2022). Diesel engines, a type of internal combustion engine, operate by using fuel auto-ignition at a high compression ratio. They are known for their superior torque and fuel efficiency, as well as their long lifespans and reliable performance at low revolutions per minute (RPMs), making them ideal for long distances and heavy loads. Gasoline engines, on the other hand, have lower upfront costs and are preferred for city driving and quick acceleration, with cheaper maintenance (AvisFilo, 2024).

The main differences lie in fuel efficiency, engine life, performance, and maintenance. Diesel engines deliver higher torque and efficiency but lower horsepower due to limited RPMs. In contrast, gasoline engines are faster and more affordable to maintain (AvisFilo, 2024).

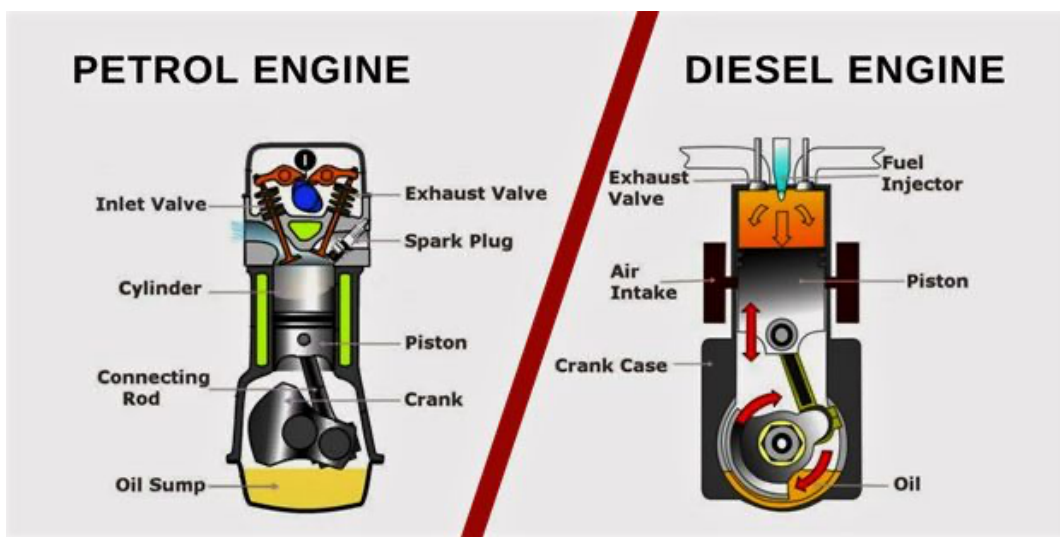


Figure 2.2: Petrol and diesel engine components (Valvoline™ Global Europe, n.d.).

The first EV is considered to be the model with an electric motor invented by Hungarian engineer Ányos Jedlik in 1828 (Muratoğlu & Alkaya, 2016). However, it

is known that Stratingh and Thomas Davenport developed new models in 1835. The first truly successful EV, however, was the electric locomotive built by Robert Davidson in 1838, capable of reaching a speed of 6.4 kilometers per hour. Despite its success, this vehicle lacked the ability to recharge (Tören & Mollahasanoglu, 2022).

In 1842, the invention of lead-acid batteries by Thomas Davenport and Robert Davidson led to a golden era for EVs in the early 1900s. By this time, 28% of the vehicles produced in the United States were electrically powered. However, the launch of Henry Ford's mass-produced ICEVs in 1908 dealt a significant blow to EVs. This was due to several factors, including the high cost of EVs (approximately three times more expensive than ICEVs), the demand for longer travel distances, lower horsepower, and the easier availability of gasoline. These challenges caused the development of EVs to be postponed until the 1960s (Tören & Mollahasanoglu, 2022).

The resurgence of interest in EVs began due to the rising number of ICEVs, the resulting air pollution, and the 1973 oil crisis. Vanguard-Sebring launched the CitiCar at the Washington Electric Vehicle Symposium in 1974. The United States then implemented policies to encourage hybrid and EV development (Tören & Mollahasanoglu, 2022).

In the 1990s, legislative efforts such as the Clean Air Act Amendments and the Energy Policy Act supported investments in this field. Between 1996 and 2000, major manufacturers like General Motors, Toyota, Honda, Ford, Nissan, and Chevy produced EVs, primarily for rental purposes. However, issues with range and charging infrastructure limited their success (Tören & Mollahasanoglu, 2022).

The game-changer came in 2008 with Tesla's introduction of a lithium-ion battery-powered vehicle. The long range and easy charging capability of Tesla's Roadster marked a new era for EVs, capturing significant attention and encouraging other automakers to enter the market. Today, nearly all major automobile manufacturers offer at least one EV model (Tören & Mollahasanoglu, 2022).

In Türkiye, the first EV was the Renault Fluence ZE, produced in Bursa in 2009. This model had a range of 185 kilometers and a charging time of 10-12 hours. A historic step was taken in late 2019 with the unveiling of Türkiye's first domestically produced EV, Türkiye's Automobile Joint Venture Group (TOGG), in a grand ceremony (Tören & Mollahasanoglu, 2022).

EVs are a viable technology for reaching a sustainable transportation sector in the future because of their low carbon emissions, low noise level, high efficiency, and flexibility in electricity mix and integration. An EV is a vehicle powered by an electric motor that draws electricity from a battery and may be charged from an external source (US Department of Energy, 2021). An EV is defined as a vehicle that can only be powered by an electric motor that pulls electricity from a battery, as well as a vehicle that can also be powered by an internal combustion engine (plug-in hybrid electric vehicle). (US Department of Energy, 2021).

EVs, in contrast, are powered by electricity stored in batteries. This eliminates tailpipe emissions and significantly reduces GHG emissions when charged with renewable or low-carbon electricity. Over the last decade, EV sales have witnessed exponential growth. According to the IEA's recent report, in 2023 EV have a share of 25% in the European passenger car market (IEA, 2024). In addition, global EV sales have surged from fewer than 1 million units in 2015 to approximately 14 million in 2023, with projections suggesting this amount could reach 17 million in 2024, accounting for more than 20% of global car sales (IEA, 2024). Türkiye's EV sales and stocks number shown in the Table 2.1. This quick adoption has been encouraged by advances in battery technology, government incentives, and increased consumer environmental awareness. There are four types of EVs which illustrated in the Figure 2.3 (Aayog, n.d.);

- i) **Battery Electric Vehicle (BEV):** BEVs are fully powered by electricity, with no internal combustion engine. These vehicles rely solely on an onboard battery, which is charged via external power sources. BEVs are the most energy-efficient type of EV, outperforming hybrids and plug-in hybrids in terms of energy use and emissions (Aayog, n.d.).
- ii) **Hybrid Electric Vehicle (HEV):** HEVs use both an internal combustion engine (often powered by gasoline) and a battery-driven electric motor. The combustion engine serves two functions: it drives the car and recharges the battery when it is empty. While HEVs have higher fuel efficiency than traditional automobiles, they are less efficient than BEVs or Plug-in Hybrid Electric automobiles (PHEVs) (Aayog, n.d.).

- iii) **Plug-in Hybrid Electric Vehicle (PHEV):** PHEVs also combine an internal combustion engine with an electric motor however unlike HEVs in that their batteries may be charged externally via a power outlet. This allows PHEVs to run on electricity for a significant portion of their trips, reducing reliance on the combustion engine. PHEVs are less efficient than BEVs, but more efficient than HEVs (Aayog, n.d.).
- iv) **Fuel Cell Electric Vehicle (FCEV):** FCEVs generate electricity through a chemical reaction, typically using hydrogen fuel. These vehicles produce electricity onboard by combining hydrogen with oxygen in a fuel cell, with water as the only byproduct. Hydrogen FCEVs are a promising technology for zero-emission transportation, especially for long-range applications (Aayog, n.d.).

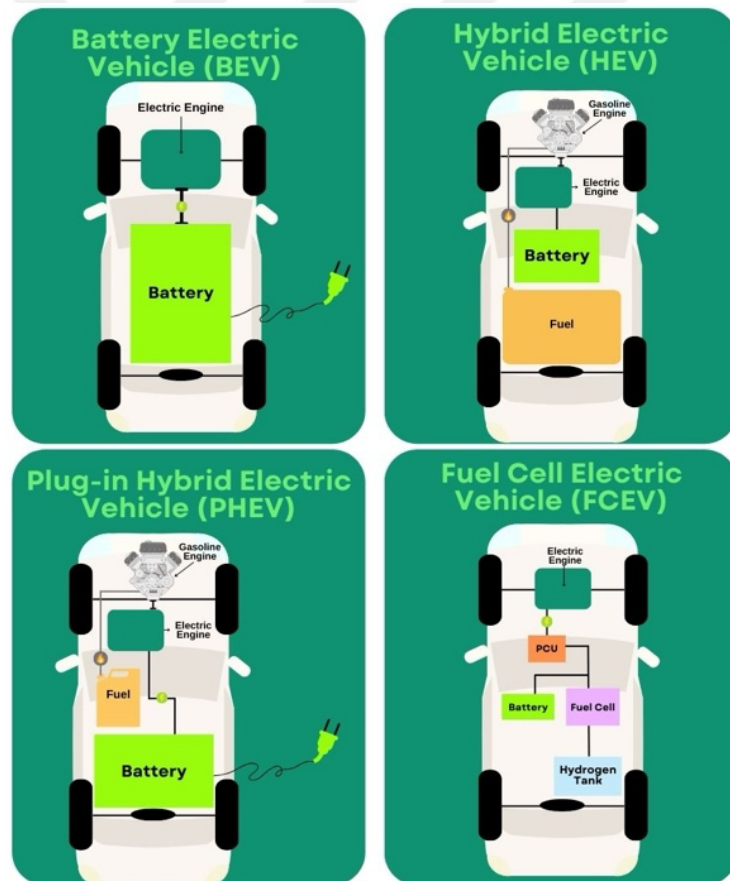


Figure 2.3: EV types and their components.

Table 2.1: EV sales and stock number by years in Türkiye (IEA, 2024).

Years	Sales	Stock
2012	92	0
2013	1	230
2014	68	260
2015	230	370
2016	127	630
2017	111	740
2018	235	930
2019	324	1840
2020	1290	3900
2021	3920	8600
2022	7540	16300
2023	68700	81900

The case for climate protection has never been stronger. Climate change is a global concern that endangers lives and economies alike. The transportation sector, which contributes significantly to GHG emissions such as CO₂, methane (CH₄), nitrous oxide (N₂O), hydrofluorocarbons (HFCs), and fluorinated gases, as well as other emissions such as carbon monoxide (CO), hydrocarbons, nitrogen oxide (NO_x), and particulate matter (PM), is regarded as a critical area for mitigation. These gases contribute to global warming by trapping heat in the atmosphere (EEA, 2024).

The relationship between the transport sector and carbon dioxide emissions, including its connection to the Kuznets environmental curve, has been widely studied.

For example, a study studied BRICS countries (Brazil, Russia, India, China, and South Africa) using panel data and discovered that gas and oil consumption in the transportation sector contributes positively to CO₂ emissions (Ferreira et al., 2021). Compared to all other sectors, GHG emissions from the transport sector in the European Union (EU) increased by 0.9% and 0.8% in 2018 and 2019, respectively. (EEA, 2024).

GHGs primarily originate from fossil fuel combustion, industrial activities, and transportation processes, leading to climate change, air quality degradation, and health risks. Legislative efforts, such as the Kyoto Protocol, Paris Agreement, and CO₂ emissions standards, aim to mitigate these impacts by reducing emissions and promoting cleaner technologies.

Furthermore, because tire and brake wear contribute significantly to PM emissions, switching from regular vehicles to EVs only minimally lessens the harm to human respiratory tracts (Xia & Li, 2022). Compared with ICEVs, EVs have a higher impact on Abiotic depletion potential (ADP), Human Toxicity Potential (HTP), and Eutrophication Potential (EP), despite their low CO₂, PM_{2.5}–PM₁₀, Sulphur dioxide (SO₂) and CO emissions (Xia & Li, 2022).

In addition to air pollution, noise generated by road traffic, railways, and aircraft is linked to health problems such as cardiovascular, sleep disturbances, and increased stress levels (Kopelias, et al., 2020). Noise annoyance, caused by both chronic and temporary exposure, has been addressed through legal frameworks like the EU Environmental Noise Directive and United States (US) regulations, which set limits on permissible noise levels. Innovative solutions, such as advanced noise barriers, are being developed to mitigate these effects and improve public health outcomes. Addressing both air and noise pollution is critical to decreasing the environmental footprint of the transportation field (Kopelias, et al., 2020).

ICEVs produce emissions like NO_x, CO, particulate matter, and Volatile Organic Compounds (VOCs), contributing to acidification, eutrophication, human toxicity, and photochemical oxidation. These emissions lead to environmental harm such as smog and health issues. While EVs do not emit direct pollutants during use, their battery production and energy source can cause indirect environmental effects, such as resource depletion and toxicity risks. However, clean energy and recycling can reduce these impacts, making EVs more environmentally friendly over their life cycle compared to ICEVs.

Implementing aggressive mitigation strategies in the transportation sector is crucial to meet the objectives of the European Green Deal, which aims to reduce GHG emissions by 55% by 2030 and achieve climate neutrality by 2050 (European Commission, 2019).

In summary, the transportation sector is a major contributor to greenhouse gas emissions and environmental pollution, but it also presents an opportunity for meaningful change. Transitioning to cleaner technologies like EVs is a step in the right direction, though challenges like battery recycling, non-exhaust emissions, and clean energy integration still need to be addressed. Beyond air pollution, tackling noise

pollution and raising public awareness about sustainable transport are key to creating healthier communities. By working together and acting decisively, we can transform transportation into a more sustainable system and meet the ambitious climate goals set by initiatives like the European Green Deal.

2.2 Life Cycle Assessment Framework

LCA possesses unique characteristics that enable it to address questions that other assessment tools cannot. Use of LCA in the late 2000s shifted the view of biofuels as being “green,” “sustainable,” or “carbon neutral,” ultimately influencing biofuel policies. LCA’s defining features categorizes into four key aspects: (1) a life cycle perspective, (2) a broad environmental scope, (3) a quantitative approach, and (4) a foundation in scientific principles (Bjørn, et al., Main Characteristics of LCA, 2017). The primary goals of LCA include new product creation and design, product development, comparison and selection of products or processes, and the analysis of service-related problems. Commonly used LCA tools to achieve these goals include Sphera's LCA for Experts (GaBi), SimaPro, GREET, CCaLC and Open LCA.

The Life Cycle Assessment (LCA) model is a structured approach for evaluating and reporting the environmental, economic, and social implications of producing or providing a product or service. This framework adheres to standards set by the International Organization for Standardization (ISO), including ISO 14040 (Environmental Management - LCA - Principles and Framework), ISO 14044 (Environmental Management - LCA - Requirements and Guidelines), and ISO 14067 (GHG - CF of Products - Requirements and Guidelines for Quantification) (ISO, 2024). LCA assesses these impacts across the entire life cycle of a product, from the extraction of raw materials to its ultimate disposal (Demirer, 2011).

LCA is strong in its comprehensive approach, evaluating the entire life cycle of a product and covering various environmental issues. This allows for comparing impacts across product systems with many processes, resource uses, and emissions at different times and locations. However, its broad scope requires simplifications and generalizations, making LCA more about estimating impact potentials rather than calculating actual impacts due to uncertainties in modeling resource use and emissions (Bjørn, et al., Main Characteristics of LCA, 2017).

LCA follows the "best estimate" principle, ensuring unbiased comparisons, but it overlooks rare but significant risks. As a result, certain risks are not considered, leading to potential misinterpretations. Lastly, while LCA can show which product is environmentally better, it cannot determine if that option is truly sustainable. Therefore, LCA should not be used to claim absolute environmental sustainability (Bjørn, et al., Main Characteristics of LCA, 2017).

The concept of LCA emerged in the 1960s as concerns about environmental degradation and resource limitations grew (Bjørn, et al., LCA History, 2017). Initially, LCA focused on packaging, energy use, and emissions, with early method development occurring primarily in the US and Northern Europe. After a quiet period in the 1970s, the 1980s and 1990s saw significant progress in LCA methodology, driven by increased international collaboration and academic involvement. As the methodology matured, LCA has evolved to include a greater range of products and systems, with studies commissioned by both industry and the government, and the findings published in academic and policy reports. Methodological development continues today, with greater emphasis on building international consensus and standardizing LCA practices (Bjørn, et al., LCA History, 2017).

LCA examines both direct impacts (e.g., emissions generated during production, energy consumption) and indirect impacts (e.g., raw material extraction, transportation, usage, and disposal) (OTEP, 2024). This comprehensive assessment approach allows industries to monitor environmental impacts, connect social consequences with cost analysis, guide investment decisions, select appropriate processes or products, and improve operations. Additionally, LCA supports product declaration, eco-labeling, marketing, and strategic planning efforts.

When conducting an LCA, the efficiency and impacts (direct or indirect) of the current production process are evaluated. Alternative processes are also assessed, enabling comparisons and the selection of the most efficient and sustainable option. Besides environmental aspects, LCA can also be applied to assess economic impacts, such as resource and energy usage.

2.2.1 Subcategories of LCA

LCA encompasses two specific subcategories:

- i) **Life Cycle Energy Analysis (LCEA):** This focuses on the energy inputs needed throughout a product's life cycle, including its manufacturing, usage, transportation, and disposal (OTEP, 2024).
- ii) **Life Cycle Cost Analysis (LCCA):** This evaluates the total costs incurred during a product's life cycle, such as initial investment, transportation, operation, maintenance, and disposal costs (OTEP, 2024).

LCA is further linked to concepts like the ecological footprint and water footprint, which enhance the environmental assessment by addressing critical resource usage and impacts (OTEP, 2024).

2.2.2 Stages of LCA

Based on ISO 14040, the LCA framework comprises four main stages (ISO, 2024) (Figure 2.4):

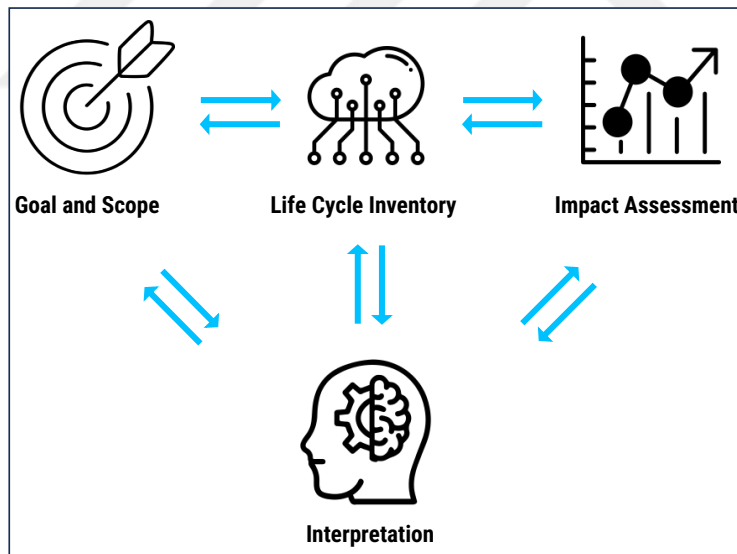


Figure 2.4: Main four stages of LCA framework.

- i) **Goal and scope definition:** This stage involves defining the purpose, scope, boundaries, and level of detail of the assessment. The functional unit, which serves as a reference point for quantifying inputs and outputs, is also determined here.

ii) Inventory analysis: This stage identifies and quantifies inputs such as energy, water, and raw materials, along with emissions associated with these inputs. It involves mapping process flows, collecting data, and evaluating and reporting results. Data quality is critical to ensure reliable outcomes. Transparency is important parameter that reflect clear and understandable presentation of information. Key aspects of data quality include (OTEP, 2024):

- **Temporal information:** When the data was collected and the duration of collection (e.g., annual, monthly).
- **Geographic information:** The geographic scope of the study (e.g., local, regional, national, global).
- **Technological information:** The nature of the technology used (e.g., best-available technology or an average of operational units).

iii) Impact assessment: This stage evaluates the environmental impacts of the inputs and emissions identified in the inventory analysis. It involves selecting and classifying impact categories, defining characterization factors, comparing potential impacts, ranking categories, and, if needed, applying weighting methods to consolidate findings. Common impact categories include:

- Global Warming Potential (GWP)
- Acidification Potential (AP)
- Eutrophication Potential (EP)
- Ozone Layer Depletion Potential (OLDP)
- Photochemical Smog Potential (PSP)
- Human Toxicity Potential (HTP)
- Fine Particulate Matter Formation (FPMF)
- Resource Depletion (RD)

The environmental mechanism in Life Cycle Impact Assessment (LCIA) begins with an environmental intervention, represented by an elementary flow in the Life Cycle Inventory (LCI). The contribution of this flow to an impact indicator is measured along the cause-effect chain of the chosen impact category. It is important to select an impact indicator based on environmental relevance rather than just measurability. For

instance, choosing human exposure as an indicator for health impacts may be misleading, as exposure does not necessarily correlate with harmful health effects if the substance is not toxic (Rosenbaum, et al., 2018).

Endpoint impact indicators are used to broaden or relate midpoint indicators to specific areas of protection (AoPs), which reflect the important societal interests that need to be protected, such as human health, ecosystems quality, and planetary life support functions (e.g., ecosystem services and resources). These indicators are chosen later in the cause-effect chain, closer to the endpoint, and reflect the broader impacts of environmental degradation (Rosenbaum, et al., 2018).

The primary endpoint indicators typically focus on:

- Human health
- Ecosystem quality or the natural environment
- Natural resources and ecosystem services

These endpoint indicators are derived from the same impact categories as midpoint indicators, but they are further refined to specify which AoP is affected. For example, climate change may have one midpoint indication but two endpoint indicators: one for human health and one for ecological quality (Rosenbaum, et al., 2018).

Each endpoint indicator within the same AoP is expressed with similar unit, and their findings can be combined to generate an overall impact score for that AoP, providing a clear overview of the total environmental impact. However, before aggregation, the environmental profile at the endpoint level is as thorough as at the midpoint level, allowing for contribution analysis to identify which impact categories contribute most to each AoP (which one most affects human health) (Figure 2.5) (Rosenbaum, et al., 2018).

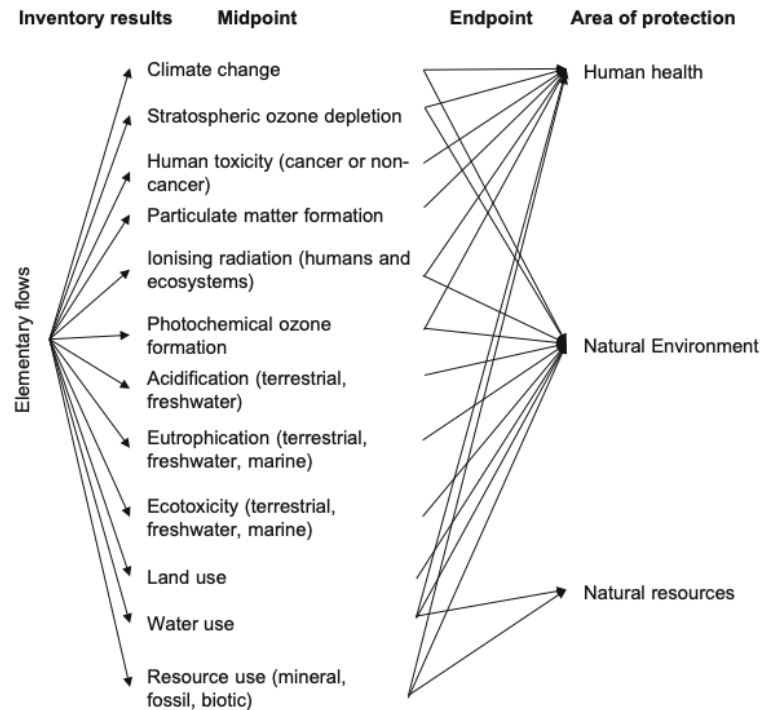


Figure 2.5: Framework of impact categories at midpoint and endpoint level (Rosenbaum, et al., 2018).

The closer an indicator is to the end of the cause-effect chain, the more relevant it is to environmental concerns, though it may also introduce more uncertainty and be harder to measure. This creates a balance between selecting early-stage indicators that are easier to measure but less relevant to actual environmental impacts and selecting later-stage indicators that are more environmentally relevant but harder to verify.

This distinction leads to two types of impact indicators: midpoint and endpoint. Midpoint indicators focus on measurable environmental effects (e.g., climate change, acidification) and group related substance flows to assess their contribution to these impacts. Endpoint indicators, on the other hand, assess the more direct consequences of environmental effects (e.g., ecosystem degradation, human health outcomes). The results of the midpoint impact assessment form a characterized impact profile, which can be used to prepare for a more detailed endpoint-level impact assessment (Rosenbaum, et al., 2018).

The LCIA methods pack organizes impact assessment methods as a collection of impact categories, aligning with the traditional understanding of LCIA methods. In LCA, users select a method before conducting calculations for a product system or

project. In this selection, the pack provides detailed descriptions of the included methodologies. A key distinction between the LCA pack and the ecoinvent pack lies in the number of characterization factors available. While the ecoinvent pack primarily includes flows and compartments specific to its database, the LCA pack incorporates flows from various databases and maps compartments more broadly. For example, if a specific characterization factor is unavailable for “air-high population density,” it defaults to the factor for “air-unspecified.” Some of these methods are as follows (Acero, et al., 2015):

- Cumulative Energy Demand
- Eco-indicator 99 (E-H-I)
- Ecological Scarcity Method 2006
- ILCD 2011 Endpoint/Midpoint
- ReCiPe endpoint/midpoint (E-H-I)
- TRACI 2.1
- USEtox
- Institute of Environmental Sciences (CML)

iv) Interpretation and reporting: In the final stage, the results are systematically analyzed, interpreted, and presented. This phase, known as the Life Cycle Interpretation stage, involves evaluating findings from the inventory analysis or impact assessment in accordance with the study's defined goals and scope. Sensitivity and uncertainty analyses are typically performed to increase the reliability of the results. Recommendations for improving processes, products, or services are provided, and comparisons are conducted to identify the most environmentally sustainable option (Rosenbaum, et al., 2018).

2.2.3 System boundaries and functional unit

Defining system boundaries is crucial in LCA to determine the processes included in the life cycle and to simplify the analysis by excluding negligible processes. Boundaries can vary:

- **Cradle to Grave:** Covers all stages, from raw material extraction to disposal.
- **Cradle to Gate:** Includes processes from raw material extraction to the production facility.

- **Cradle to Cradle:** Includes recycling and recovery processes.
- **Gate to Gate:** Focuses only on production and distribution stages.

The **functional unit** serves as a quantitative reference for comparing LCA results. For vehicles, this is often defined as “per kilometer” (e.g., 1 km traveled) or “per passenger-kilometer.” For batteries, it is typically expressed as “per kilowatt-hour (kWh) of energy.”

2.3 Relationship between LCA and Vehicles

LCA is a strong technique for assessing the environmental effect of products over their entire life cycle, from raw material extraction to disposal. When applied to automobiles, LCA offers vital insights into the sustainability of various modes of transportation, such as EVs and ICEVs. This section looks at how LCA concepts can be used to compare and evaluate vehicle environmental footprints, emphasizing their importance in designing a cleaner, more sustainable transportation future. Average CO₂ emission values of vehicle fuel type are given in the Table 2.2.

Table 2.2: Average CO₂ emission values of vehicle fuel type (Tören & Mollahasanoglu, 2022).

Fuel Type	CO ₂ Emission Value (g/km)
Gasoline	174.31
Diesel	168.43
Liquefied Petroleum Gas (LPG)	198.28
Hybrid*	119.52
Hybrid (rechargeable)	71.00
Electric	0

* Hybrid (internal combustion engine + electric motor)

Övez et al. (2023) conducted a review, a total of 40 LCA articles were identified, but only 15 were analyzed due to specific criteria such as functional unit, system boundaries, and impact categories. Among these, 5 were from 2019, and 5 from 2022, with the SimaPro model being the most used LCA tool. Literature review included 15 articles, highlighting GWP, acidification, eutrophication, and human toxicity as the most assessed impact categories, while land use and water use were the least studied.

The most examined battery technologies were lithium-ion and nickel cobalt manganese batteries. The most frequently used tool in the review is SimaPro, which is included in 4 articles. SimaPro is followed by GaBi, which is used in 3 articles, and CCaLC, which is used in 1 article. Using different tools may affect the comparability of LCA results, as well as revealing the differences in data and functions provided by these tools (Övez, et al., 2023).

According to Wu et al. (2018), the life cycle GHG emissions of BEVs and conventional ICEVs were calculated and compared under China's energy production mix scenarios for 2010 and 2014. The ICEV emissions were determined to be 34.9 tCO₂eq/vehicle with the 2010 mix and 29.7 tCO₂eq/vehicle with the 2014 mix. In contrast, the BEV emissions were 42.5 tCO₂eq/vehicle for the 2010 mix and 31.4 tCO₂eq/vehicle for the 2014 mix (Wu, et al., 2018).

The cradle-to-grave approach encompasses the manufacturing, use, and recycling stages of EVs and ICEVs to evaluate their entire life cycle (Tagliaferri, et al., 2016). In the production phase, EVs produce between 14.6 and 14.7 tons of CO₂, which is around 60% higher than the 9.2 tons emitted by ICEVs (Qiao, et al., 2017). A significant portion of these emissions comes from battery production, a major contributor to GHG emissions in EV manufacturing (Kim, et al., 2016). Girardi et al. (2015) also noted that EV and battery production result in higher GHG emissions and other environmental impacts compared to ICEVs.

In the use phase, EVs have a lesser environmental impact, owing to the composition of the electricity grid. Cleaner energy sources in the power grid reduce the GHG emissions of EVs, offsetting their higher production-stage emissions. Furthermore, battery recycling increases resource efficiency and lowers GHG and SO₂ emissions. EVs use less fossil fuel and emit fewer GHGs over their lifetime than ICEVs. However, they outperform ICEVs in terms of environmental effect, specifically EP, HTP, and particulate matter generation (Qiao, et al., 2020; Burchart-Korol, et al., 2018).

In addition, while battery production increases the environmental burden during the manufacturing phase of EVs, cleaner energy sources and improved recycling processes significantly enhance their environmental performance during use and end-of-life stages. EVs reduce fossil fuel usage and GHG emissions throughout their life cycle.

However, the intensive use of mineral and metal resources in battery manufacture raises the consequences on abiotic depletion potential (ADP) and HTP. (Dolganova, et al., 2020; Verma, et al., 2021). Thus, improving mineral resource efficiency, advancing battery production technologies, incorporating cleaner energy, and fostering battery reuse and recycling industries are critical for the sustainable growth and widespread adoption of EVs.

In another study compares the environmental impacts of EVs and ICEVs produced in Türkiye using LCA (Üçtuğ, 2022). While EVs are found to be more environmentally friendly in terms of CF, the total environmental impact score, calculated through equal weighting, reveals that EVs have a 4% higher impact than internal combustion vehicles (Üçtuğ, 2022). Increasing the share of renewable energy in Türkiye's electricity grid is essential to reduce the non-carbon environmental impacts of EVs (Üçtuğ, 2022). The life cycle impacts of EVs primarily stem from raw material supply (52.7%), usage and disposal (43.9%), with minimal contributions from production (3.2%) and transportation (0.2%) (Üçtuğ, 2022). Key contributors to environmental impacts are electricity consumption during operation and tire usage, dominating categories like CF, acidification, and EP (Üçtuğ, 2022). For ICEVs, raw material supply (84.3%) and usage and disposal (10.2%) are the main contributors, with tires and gasoline being primary drivers (Üçtuğ, 2022). ICEVs differ in that direct emissions during use and indirect emissions from fuel production contribute significantly to their environmental footprint (Üçtuğ, 2022). Reducing electricity's impact is critical for EV sustainability, especially in countries like Türkiye, where fossil fuels dominate electricity generation (Üçtuğ, 2022).

Building upon findings from prior studies, this thesis refines the analysis by focusing on a structured evaluation of environmental impact categories specific to Turkey's context for the next 25 years. The outcomes aim to provide actionable insights for policymakers and stakeholders, emphasizing the importance of informed decision-making in transitioning to sustainable transportation systems.

The importance of LCA is shown by its inclusion into global programs such as the United Nations Sustainable Development Goals (SDGs) (United Nations, 2015), the European Union Circular Economy Action Plan (European Commission, 2015), and the European Green Deal. (European Commission, 2019).

- Companies aiming to market their products in the EU are mandated to disclose their environmental performance.
- The European Commission has proposed methods such as the Product Environmental Footprint (PEF) and the Organizational Environmental Footprint (OEF), both of which are grounded in LCA principles.

These developments highlight the growing significance of LCA in environmental management and policy-making.



3. MATERIALS AND METHODS

This study consists of three main stages, each employing distinct methods and tools to achieve the research objectives (Figure 3.1). In the first stage, a scientific projection study was conducted to gather data on Türkiye's energy and electricity production mix for the years 2020 to 2050. These data were compiled, organized, and prepared for use in the subsequent stages of the research.

The second stage involved modeling and analysis using the CCaLC tool. System boundaries were defined, and necessary assumptions were incorporated to ensure a comprehensive LCA. The model was executed to generate results based on the defined scenarios and energy mix data.

Finally, in the third stage, expert opinions were collected through a structured survey. Using the feedback from experts, a weighting method was applied to aggregate six different impact factors into a single value. This step enabled a comparative evaluation of the environmental impacts of each scenario, providing critical insights for the analysis. Each stage contributes uniquely to achieving the overall aim of assessing and comparing the life cycle impacts of EVs and ICEVs in Türkiye under various electricity production scenarios.

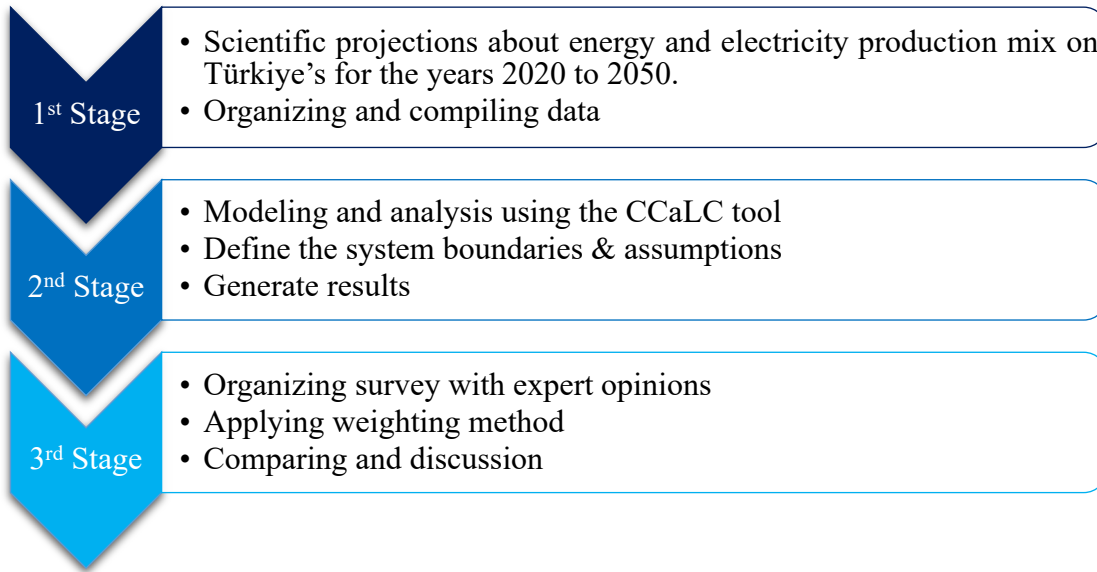


Figure 3.1: Methodology stages of the thesis.

3.1 Electricity Production Mix Projections

Using the dataset by (Garaffa, et al., 2022), scenarios for the distribution of electricity generation sources (ktoe) in Türkiye between 2020 and 2050, with 5-year intervals, have been prepared and organized to obtain electricity mix projections.

The Social Accounting Matrix (SAM) extends Leontief's input-output tables, which were developed to illustrate the interdependencies of economic agents (Figure 3.2). The SAM is a statistical framework that systematically records the production, consumption, and income distribution within an economy. It is represented as a square matrix, where columns reflect expenditures and rows represent receipts, ensuring that expenditures and receipts are balanced for each commodity (Capros, et al., 2013).

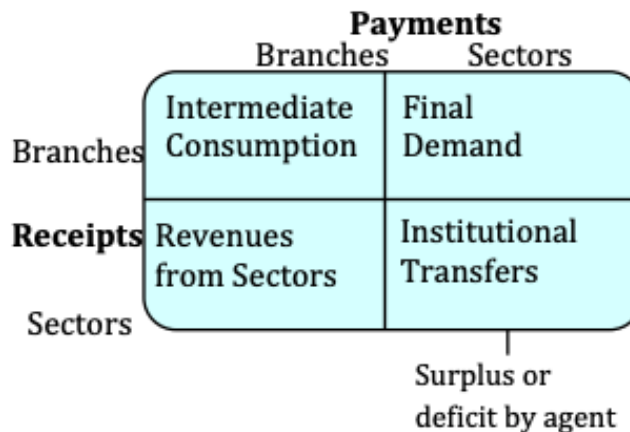


Figure 3.2: The Social Accounting Matrix (Capros, et al., 2013).

For the thesis, the energy supply mix database is utilized, which operates as a form of SAM. In this part of the thesis, this data will be used to evaluate how energy supply and demand dynamics influence sustainability efforts, particularly in the context of EVs and waste-to-energy strategies (Capros, et al., 2013).

In the processed data:

1. The values for *coal* and *coal fired* are summed and presented under the category *coal*.
2. The values for *oil products*, *crude oil*, and *oil fired* are combined into the category *oil*.
3. The values for *gas* and *gas fired* are aggregated under the category *gas*.

This organization provides a simplified representation of Türkiye's electricity generation source distribution for the selected periods.

Figure 3.3 shows the change in the mix of energy sources used in electricity production between 2020 and 2050 as a percentage. While coal constituted 35% (9837 ktoe) of electricity production in 2020, it decreased to 25% (21872 ktoe) in 2050. Coal is a fossil fuel that causes high carbon emissions. The acceleration of the transition to renewable energy sources and the adoption of carbon neutrality targets are reducing coal use. Oil, which was 1% in 2020, will be close to zero by 2050. Oil is generally a high-cost option in electricity production. In addition, environmental impacts and the transition to renewable energy make oil use unnecessary. Natural Gas, which was 24% in 2020, decreases to 7% in 2050. Although natural gas does not have as high carbon emissions as other fossil fuels, it is giving way to renewable energy in line with sustainable energy targets. Nuclear Energy, which there was no share in 2020, increases to 2% in 2050. Nuclear energy is a low-carbon energy source and is preferred to increase energy security. It also meets base load production by being supported by renewable energy. Biomass shows a slight decrease from 5% to <1%. Since it is carbon neutral, biomass energy sources play a supporting role in renewable energy systems. Hydroelectricity, which was 24% (6715 ktoe) in 2020, decreases to 15% (13616 ktoe) in 2050. The limited potential of hydroelectric energy sources and the decrease in water resources due to climate change cause this decrease. Wind Energy shows a great increase from 8% to 19%. Wind energy has gained an important place in energy policies due to its low cost and renewable nature. Technological advances and

government incentives support this increase. Solar Energy, which was 3% in 2020, reaches the highest share with 31% in 2050. Solar energy is the most prominent energy source of the future thanks to its low cost, high efficiency and wide-scale applicability. Figure 3.3 shows that the share of fossil fuels in energy production is decreasing, while renewable energy sources are increasing rapidly. Also, electricity production values by source are given in Table A. 1 under the APPENDICES at ktoe level. This is a result of sustainable energy policies, carbon emission reduction targets and technological innovations. Nuclear energy is on the rise as an important option for base load energy production.

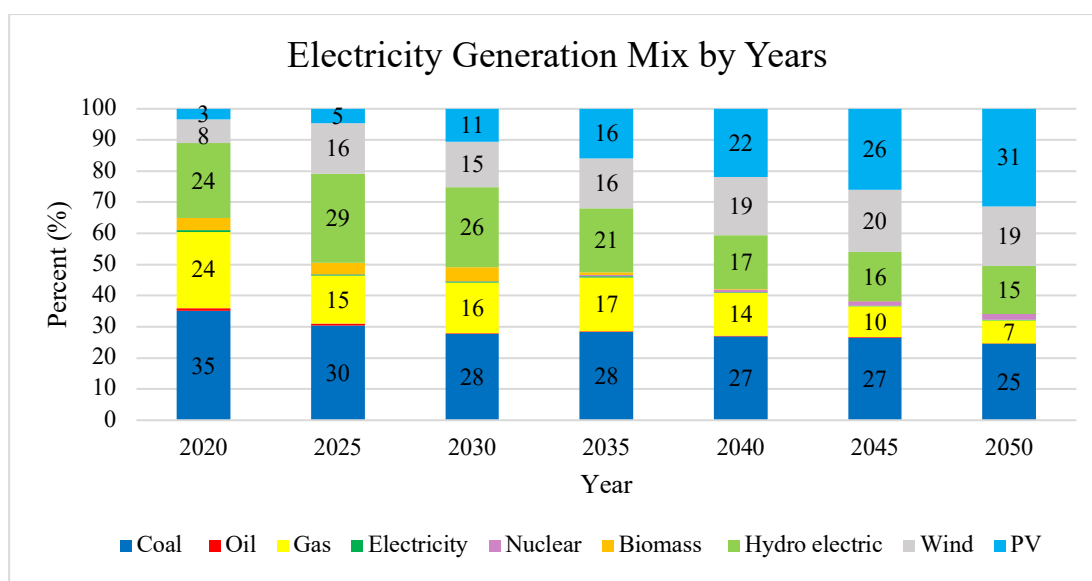


Figure 3.3: Electricity Generation Mix by years.

3.2 LCA Methodology

In this study, the CCaLC tool (Figure 3.4), developed by the University of Manchester (CCaLC, 2016), was utilized in combination with the CML 2001 methodology (Hischier & Weidama, 2010). Background data for the analysis were obtained from the Ecoinvent2 database. The environmental impacts required for the LCA study were calculated within the framework of ISO 14040 and ISO 14044 standards.



Figure 3.4: CCaLC tool.

The CCaLC tool is a user-friendly software designed for LCA. It helps analyze the carbon and water footprints of a product or system across its entire life cycle. The interface is structured to facilitate ease of use, offering a clear visualization of key environmental impacts at each phase (Figure 3.5). At the top, there are several buttons that allow users to:

- Enter system details,
- Switch between CF and water footprint analyses,
- View graphs, data quality, cumulative energy use, and other environmental impacts.

In the center, the tool breaks the life cycle into four main stages: Raw Materials, Production, Storage, Use. Each stage is displayed clearly and shows impact values for carbon emissions and water usage. There's also a section for Waste Management, highlighting the end-of-life phase of a product.

The tool uses simple color codes; red for CF and green for water usage. At the bottom, it can be seen the summary values:

- The Total CF in kg CO₂ equivalent per functional unit,
- The Total Water Usage in cubic meters per functional unit,
- The Total Water Footprint, which accounts for water stress impacts.

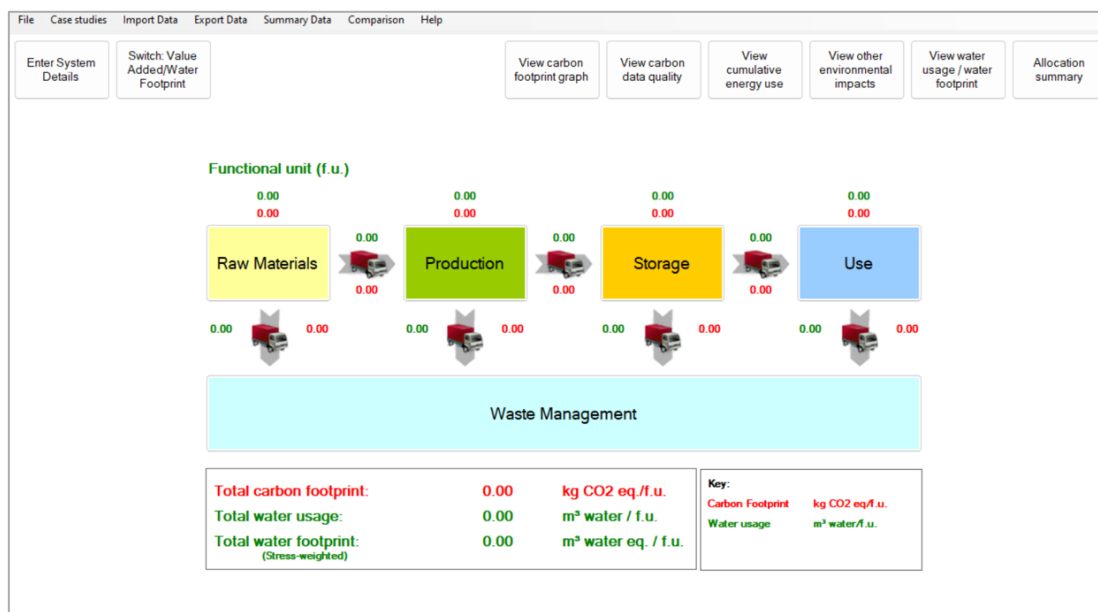


Figure 3.5: CCaLC tool interface.

The impacts considered in this study, which can be evaluated using CCaLC2, include GWP, AP, EP, PSP, OLDP, and HTP.

Developed by the University of Leiden in the Netherlands in 2001, CML includes over 1,700 distinct flows available for download from their official website. It is documented in a handbook authored by several contributors. The method is categorized into baseline and non-baseline groups, with the baseline representing the most frequently used impact categories in LCA. Table 3.1 outlines the included baseline categories (Acero, et al., 2015):

Table 3.1: Impact categories included in CML (baseline) (Acero, et al., 2015).

Impact category group	Name of the impact category in the method
Acidification	AP - average Europe
Climate change	Climate change - GWP100
Depletion of abiotic resources	Depletion of abiotic resources - elements, ultimate reserves Depletion of abiotic resources - fossil fuels
Ecotoxicity	Freshwater aquatic ecotoxicity - FAETP inf Marine aquatic ecotoxicity - MAETP inf Terrestrial ecotoxicity - TETP inf
Eutrophication	Eutrophication - generic
Human toxicity	Human toxicity - HTP inf
Ozone layer depletion	Ozone layer depletion - OLDP steady state
Photochemical oxidation	Photochemical oxidation - high NO _x

3.2.1 Goal and scope definition

The aim of this study is to compare the environmental impacts of a ICEV and an EV in the same class in Türkiye, according to the distribution of electricity generation resources in different years, using the LCA method.

The functional unit was chosen so that the environmental impact caused by vehicles throughout their lifetime is expressed in terms of the distance they travel per kilometer (km). In other words, after calculating the environmental impact values in all processes starting from the raw material required for the production of vehicles to their disposal at the end of their use, the environmental impact values were divided by the total kilometers traveled by the vehicles throughout their lifetime and the impact values per km were reported.

The scope of this study includes the following for a ICEV and an EV under Türkiye conditions:

- Raw material supply
- Battery and vehicle production and assembly
- Transportation
- Vehicle use and maintenance
- Vehicle and battery disposal

The establishment of the national infrastructure required for charging EVs is not included in the system boundaries. The boundaries of the study are summarized in Figure 3.6.

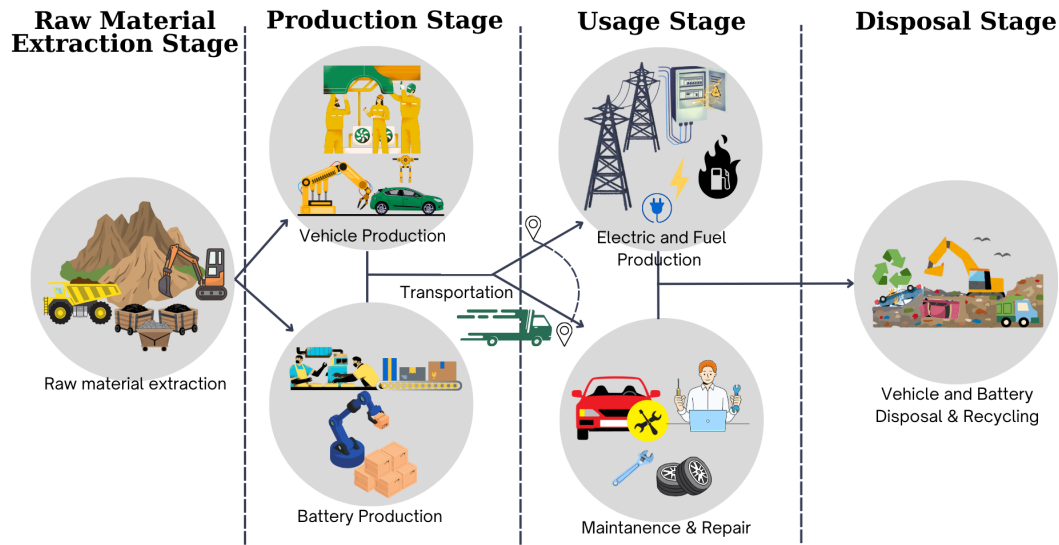


Figure 3.6: System boundaries of the thesis.

3.2.2 Life cycle inventory

As previously mentioned, the life cycle inventory in this study was developed by considering raw material production, vehicle manufacturing and assembly, transportation of intermediate and final products, usage, and disposal phases, adopting a "cradle-to-grave" approach. In other words, the study follows a comprehensive lifecycle perspective. The assumptions made during the establishment of the life cycle inventory and the creation of the life cycle model are as follows:

- **Vehicle Selection:** A sedan-type passenger car was chosen, with estimated dimensions of 4.5 meters $\times$ 1.8 meters $\times$ 1.5 meters and an estimated weight of 1.5 tons.
- **Vehicle Lifespan and Usage:** The lifespan of a gasoline-powered ICEV is assumed to be 20 years and 400,000 kilometers, while an EV is assumed to have a lifespan of 15 years and 300,000 kilometers (MYEV, 2019). Consequently, the annual usage for both vehicles is considered to be 20,000 kilometers.
- **Tire Lifespan:** Car tires are assumed to have a lifespan of approximately 65,000 kilometers. Based on this assumption, a total of six sets of tires are expected to be used over the lifetime of the ICEVs and five sets for the EV.

- **Fuel and Energy Consumption:** The average fuel consumption for the ICEVs is assumed to be 5.6 liters per 100 kilometers, while the average energy consumption for the EV is assumed to be 10 kWh per 100 kilometers (Yang, et al., 2021).
- **Manufacturing Location:** It is assumed that all parts of both vehicles, except for the EV battery, are manufactured in Türkiye. The EV battery is assumed to be imported from China.
- **Recycling Rate:** A recycling rate of 7%, which is the average recycling rate in Türkiye, is assumed for the disposal phase (Yeşiltaylar, 2018).
- **Transportation Distance:** A transport distance of 200 kilometers is assumed for delivering completed cars from the factory to the sales point. This value was randomly selected to determine whether the transportation phase impacts environmental effects.
- **Additional Inputs:** During the life cycle inventory development, two inputs not present in the Ecoinvent 2 database were identified: lead-acid batteries and car wheels. Environmental impact values for these inputs were sourced from the literature and incorporated into the CCaLC database (Premrudee, et al., 2013; Dong, et al., 2021).

Since the CCaLC2 database does not include any data on electricity in Türkiye, data which prepared and organized for the entries specified as "Electricity in Türkiye" were manually entered into. SAM GEME3 energy supply dataset was used for the "Electricity in Türkiye". The electricity mix only affects the usage phase of the vehicles. Electricity used in transportation and raw material extraction is neglected.

For the electricity consumption values within the life cycle inventory, instead of using generic data, the study utilized data from an article that reported the environmental impacts of the Turkish grid electricity calculated through LCA (Atilgan & Azapagic, 2015) (Atilgan & Azapagic, 2016 (a)). The environmental impacts of renewable electricity production were derived from the article on Atilgan and Azapagic 2016 (a). The environmental impacts of electricity produced from fossil fuels were based on the article on (Atilgan & Azapagic, 2015). The values obtained from these articles were entered into the CCaLC database, thereby enhancing the ability of the results to accurately represent Türkiye's conditions. However, the categories of electricity

production in the SAM GEME3 dataset did not match those in the articles. To use the energy data, as the first step, unit conversion was performed on the six different environmental impact categories obtained from the articles, using MJ as the unit (1 kWh = 3.6 megajoules).

For the production sources 'electricity, biomass, PV, oil, nuclear' that were not included in the articles but are present in the SAM GEME3 dataset, the following steps were followed:

- For **biomass**, The impact value for biomass was calculated by weighting the agricultural and wood contributions at 80% and 20%, respectively, based on the CCaLC database (Toklu, 2017).
- For **PV**, data from the CCaLC database specific to Türkiye was used.
- For **electricity**, data from the CCaLC database specific to Europe was used.
- For **nuclear**, data from the CCaLC database for the following countries was used to calculate the average: Canada (CN), France (FR), United Center for Electricity (UCTE), United States (USA), Switzerland (CH), and Germany (DE). The average value was considered in the calculation.
- For **oil**, data from the CCaLC database specific to UCTE was used.

For the production sources "Lignite, hard coal, small reservoir, large reservoir and runoff river" that were not included in the SAM GEME3 dataset, but are included in the articles, the following steps were followed:

- For **Lignite and hard coal**: The impact value for coal was calculated by weighting the lignite and hard coal contributions at 36% and 64%, respectively, based on the CCaLC database. Based on the TEİAŞ (2020) data, it was calculated that Lignite and Imported Coal, as well as Hard Coal + Asphaltite, have respective shares of 36% and 64% (TEİAŞ, 2020)
- Based on the TEİAŞ (2020) data, it was calculated that the share of Reservoir-based **Hydroelectric** (large and small reservoirs) is 74%, and the share of Lake and Run-of-River Hydroelectric is 26%. The distribution within the Large Reservoir and Small Reservoir categories is assumed to be equal, with each having a 37% share.

- It is assumed that the TEİAŞ (2020) data remains the same for other years and all data given in the Table A. 2 under APPENDICES.

The life cycle inventories for EVs and ICEVs are presented in Table A. 3 and Table A. 4 under APPENDICES, respectively.

3.2.3 Data quality analysis

In life cycle inventory (LCI) analysis, evaluating data quality is crucial. This process examines several factors, including reliability, completeness, temporal and geographical relevance, and technological alignment. Data must be assessed before being used in LCI to ensure reliable results. The goal is to confirm the accuracy, completeness, and reliability of the data to enable a precise environmental impact assessment of a product or process. A data quality assessment matrix is shown in Table 3.2.

Table 3.2: Data quality assessment matrix (Bicalho, et al., 2017).

Indicator Score	1 (Excellent)	2 (Very Good)	3 (Good)	4 (Fair)	5 (Poor)
Reliability	Verified data based on measurements	Verified data partly based on assumptions or non-verified data based on measurements	Non-verified data partly based on assumptions	Qualified estimate	Non-qualified estimate
Completeness	Representative data from all sites relevant for the market considered, over an adequate period to even out normal fluctuations	Representative data from >50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations	Representative data from only some sites (50% of sites but from shorter periods)	Representative data from only one site relevant for the market considered or some sites but from shorter periods	Representative unknown or data from a small number of sites and from shorter periods
Temporal Correlation	≤3 years of difference to year of study	3 to 6 years difference	5 to 10 years difference	10 to 15 years of difference	Unknown or ≥15 years of difference
Geographical Correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown area or area with very different production conditions
Further Technological Correlation	Data from enterprises, processes, and materials under study	Data from processes and materials under study but from different enterprises	Data from processes and materials under study but from different technology	Data on related processes or materials but same technology	Data on related processes or materials but different technology

In this thesis, based on the data used, it is evaluated that the reliability is very good (2), completeness is very good (2), temporal correlation is good (3), geographical

correlation is good (3), and technological correlation is excellent (2). Thus, the average data quality was found to be very good (2). In the CCaLC tool, it offers three options for data quality: High, Medium, and Low. Due to the factors mentioned above, the data quality has been determined to be Medium.

3.3 Normalization

Normalization is a critical preprocessing step in machine learning to ensure that features with differing scales do not disproportionately influence model performance. Without normalization, features with larger scales can dominate others, skewing results. Normalization equalizes feature scales, making them comparable and preventing one feature from disproportionately affecting the analysis. There are different normalization methods (Bjørn, et al., 2017).

In this study, the CML midpoint methodology was employed to compare the LCA results of EV and ICEV. To ensure comparability between the results of the six different impact categories analyzed, normalization was conducted. During the normalization process, the calculated values for each impact category were divided by the reference values provided by the CML 2001 baseline methodology. This approach transforms the results into dimensionless values, enabling a clearer and more consistent interpretation of environmental impacts. Following the normalization step, these values will be aggregated into a single indicator using a weighting method. This approach aims to prioritize impact categories and contribute to decision-making processes.

Table 3.3: Normalization factors by impact factors (CML, 2001).

Environmental themes	Normalization factors
Global warming (kg CO ₂ eq./yr)	4.18E+13
Abiotic depletion (kg Sb eq./yr)	1.83E+11
Ozone layer depletion (kg CFC-11 eq./yr)	2.30E+08
Human toxicity (kg 1,4 DB eq./yr)	3.82E+13
Fresh water ecotoxicity (kg 1,4 DB eq./yr)	3.48E+12
Terrestrial ecotoxicity (kg 1,4 DB eq./yr)	1.09E+11
Photochemical oxidation (kg ethylene (C ₂ H ₄) eq./yr)	5.44E+10
Acidification (kg SO ₂ eq./yr)	2.39E+11
Eutrophication (kg PO ₄ eq./yr)	1.58E+11

Normalized results calculation by using normalization factor is shown in the equation (3.1).

$$\text{Normalized Results} = \frac{\text{Calculated Results}}{\text{Normalization Factor}} \quad (3.1)$$

3.4 Survey Development

In this thesis, a survey was designed and conducted to determine the weighting factors for six different impact categories identified in the LCA of electric and ICEVs. The survey collected expert opinions to assign weights to each impact category, reflecting their relative significance. Using these weights, the normalized values of the six impact categories were aggregated into a single weighted score for each vehicle type. This unified score facilitates a direct comparison between EVs and ICEVs in terms of their overall environmental impact. The methodology ensures a comprehensive and balanced evaluation by integrating expert-driven weighting into the decision-making process.

The survey was prepared using Google Forms under the title “Determining the Importance of Environmental Impact Factors for Electric and Internal Combustion Engine (Gasoline or Diesel) Vehicles”. The survey link was shared with participants via email, ensuring efficient and direct access. The survey was sent to approximately 100 experts. Participants were given 1 month to answer the survey. It took approximately 5–6 minutes to complete the survey, which consisted of a mix of short-answer and multiple-choice questions, allowing for ease of response.

The survey included the following seven questions:

1. What is your profession?
2. What is your title?
3. How many years of experience do you have in your profession?
4. Do you own a vehicle?
5. What type of vehicle do you own?
6. Rank the following environmental impact factors from 1 to 6 based on their significance in the LCA of electric and internal combustion engine vehicles (1 = Least Important, 6 = Most Important).

7. Do you think there is another important environmental impact factor in the LCA of electric and internal combustion engine vehicles? If yes, please specify:

A total of 54 participants, exceeding the initial target of 50, provided responses to the survey. The target group consisted of environmental engineers with expertise in the field, ensuring a relevant and informed perspective.



4. RESULTS AND DISCUSSION

This section presents the findings of the LCA conducted to compare the environmental impacts of EVs and ICEVs. The study evaluates six distinct impact categories, incorporating both normalized and weighted values derived from expert feedback. By applying a comprehensive weighting methodology, the environmental performance of each vehicle type is summarized into a single indicator, enabling a clear comparison. The results are further analyzed to assess the environmental advantages and trade-offs of EVs under different electricity generation scenarios projected for Türkiye between 2020 and 2050.

4.1 Energy and Electricity Mix

The electricity generation trends in Türkiye between 2020 and 2025, illustrated in the Figure 4.1, demonstrate these dynamics. The graph shows how total electricity production (in ktoe) has changed from 2020 to 2050 and the contribution of different energy sources to this total.

While coal's share in total electricity production decreases, its absolute usage rises from approximately 12,000 ktoe in 2020 to 22,500 ktoe in 2050 due to overall increases in electricity demand. This underscores the need to limit coal usage in energy policies. Oil, contributing minimally in 2020, is nearly phased out by 2050, reflecting economic and environmental factors. Natural gas use grows modestly, from 8,000 ktoe in 2020 to 13,500 ktoe in 2050. Despite being a transitional energy source due to lower carbon emissions than other fossil fuels, its role diminishes as renewables expand. Nuclear energy, starting at 3,000 ktoe in 2020, surges to 17,000 ktoe by 2050, driven by goals to reduce carbon emissions and its advantages in energy security and consistent output. Biomass energy sees slight growth, reaching 2,700 ktoe in 2050, maintaining a limited contribution despite its carbon-neutral benefits. Hydroelectric energy production grows from 8,000 ktoe in 2020 to 14,500 ktoe in 2050, though constrained by water resource limitations. Wind energy increases from 4,000 ktoe in 2020 to 23,000 ktoe in 2050, driven by cost advantages and technological

advancements, making it a leading renewable energy source. Solar energy, starting at 1,000 ktoe in 2020, becomes the largest contributor to electricity production at 28,000 ktoe in 2050, benefiting from declining costs and supportive sustainable energy policies. In short, rise in electricity production has occurred in response to increasing energy demand. However, the fact that renewable energy sources (solar and wind) are at the forefront in meeting this demand indicates a sustainable and low-carbon energy transition.

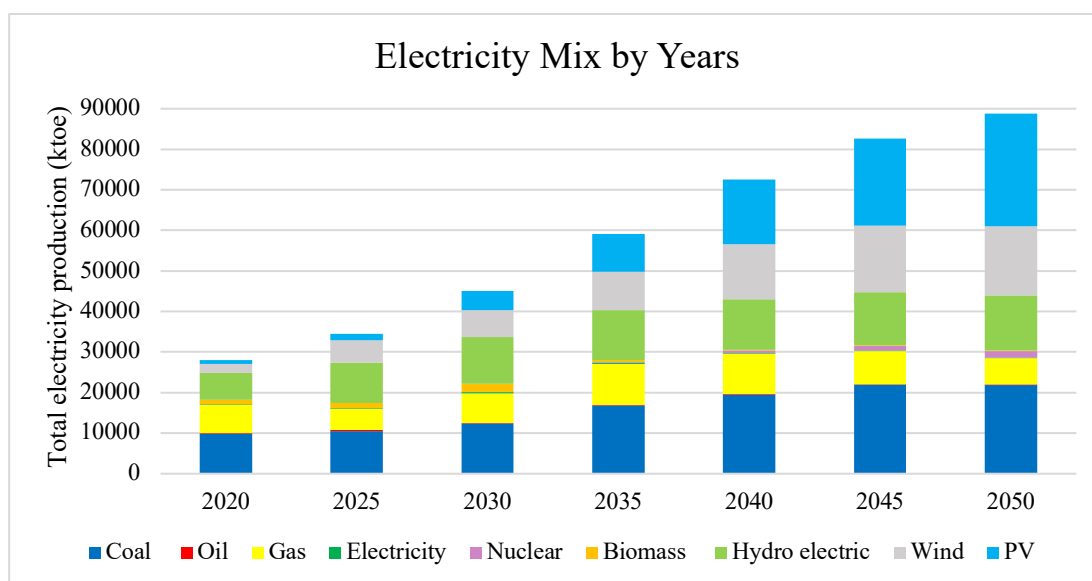


Figure 4.1: Total electricity production projection (in ktoe) from 2020 to 2050 in Türkiye.

4.2 Life Cycle Impact Analysis

This section outlines the life cycle impact results derived from the LCA of EVs and ICEVs. The impacts results are categorized into six key areas: GWP, AP, EP, PSP, OLDP, and HTP.

4.2.1 Global warming potential

Figure 4.2 presents the GWP results from 2020 to 2050 for EV and ICEV. As depicted in Figure 4.2, the GWP values for ICEVs have remained consistently higher across all evaluated years that ICEVs contribute more significantly to GHG emissions over time. For example, in 2020, the GWP of EVs was around 40,000 kg CO₂ equivalent (eq)/functional unit (f.u.), while that of ICEVs was around 90,000 kg CO₂ equivalent/f.u. This trend suggests that the reliance on fossil fuels in ICEV results in

greater emissions compared to the more sustainable practices associated with EVs, which are expected to decrease over time as technology advances and renewable energy sources are increasingly utilized. Furthermore, a decline in GWP is observed over the years for both vehicle types, with a more pronounced reduction for EVs. The majority of GWP emissions are generated during the use phase and raw material extraction stages. Overall, the data suggests a decrease in both GWP for EVs over the years, reflecting a shift towards cleaner technologies and more sustainable practices in transportation.

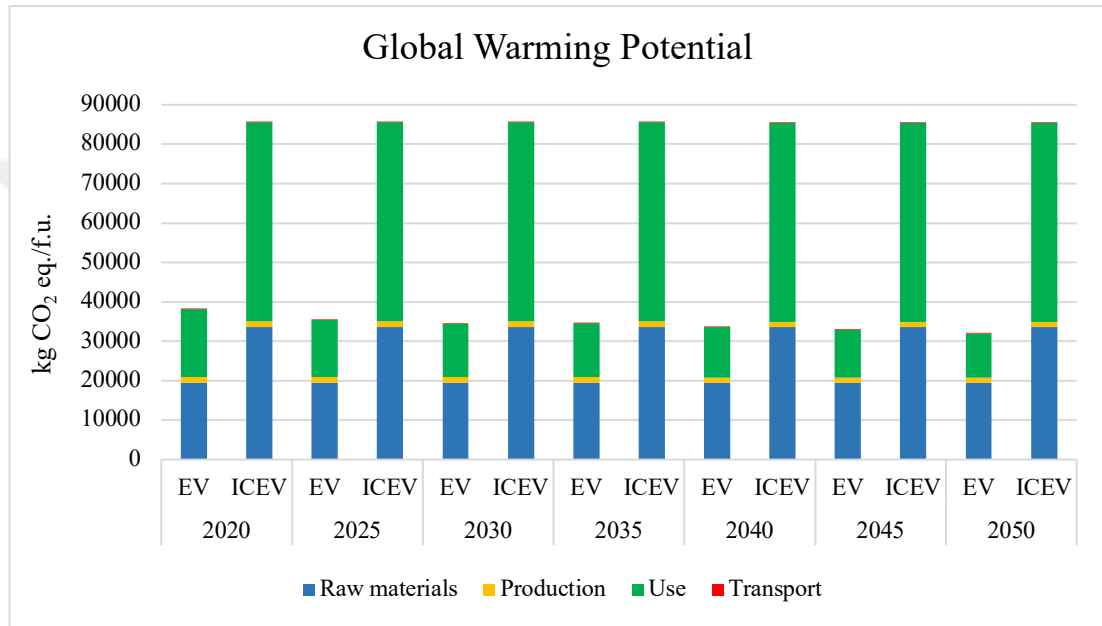


Figure 4.2: GWP by years for both EV and ICEV.

4.2.2 Acidification potential

Figure 4.3 shows that the AP results across different years from 2020 to 2050 for EV and ICEV. In 2020, the AP of EV is around 180 kg SO₂ eq/f.u., while that of ICEV is 160 kg SO₂ eq/f.u. By 2050, the AP of EV is expected to decrease (~150 kg SO₂ eq/f.u.) further, while the AP of ICEV is expected to remain high (~159 kg SO₂ eq/f.u.). This indicates that EVs have lower environmental impacts and present a more sustainable alternative for mitigating acidification, particularly when Türkiye's electricity mix is composed predominantly of renewable energy sources.

Moreover, while nearly half of the total AP for EVs is attributed to the use phase, the use phase of ICEVs contributes almost negligibly to their overall AP. The highest potential for ICEVs occurs at the raw material extraction stage.

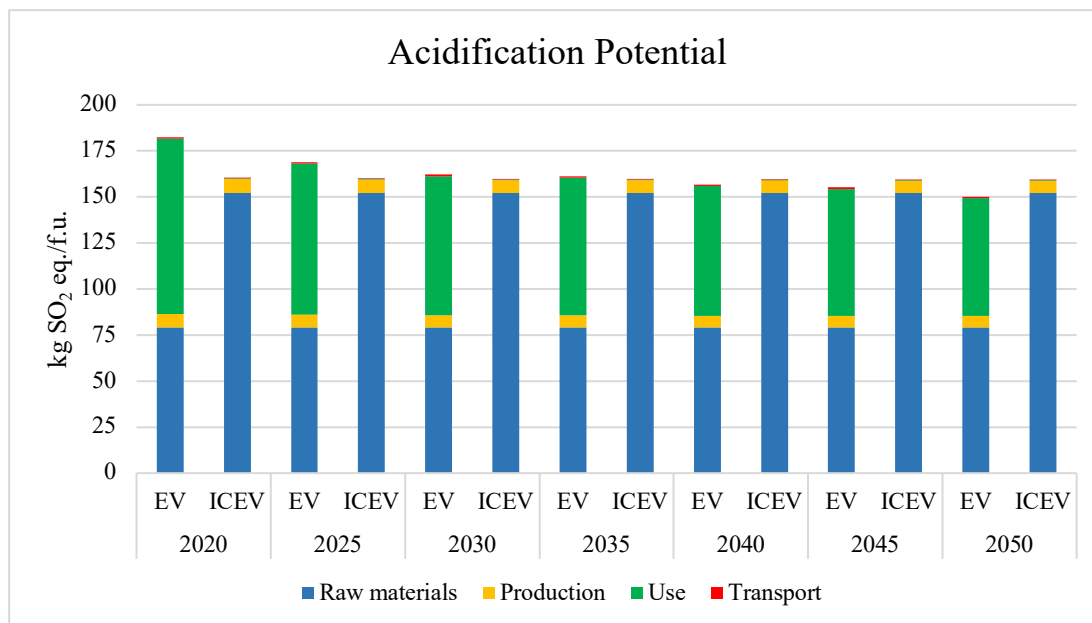


Figure 4.3: AP by years for both EV and ICEV.

4.2.3 Eutrophication potential

Figure 4.4 illustrates the EP measured in kg PO₄ eq./f.u. for both EV and ICEV from 2020 to 2050. Figure 4.4 indicates that the EP for EVs appears to be higher than that of ICEVs across all years. The trends suggest a gradual decrease in EP for both vehicle types, with EVs consistently exhibiting a decrease. The values range from approximately 70 to 90 kg PO₄ eq./f.u., highlighting the environmental effects of EVs in mitigating nutrient pollution when the values remain around 25 kg PO₄ eq./f.u. for ICEVs.

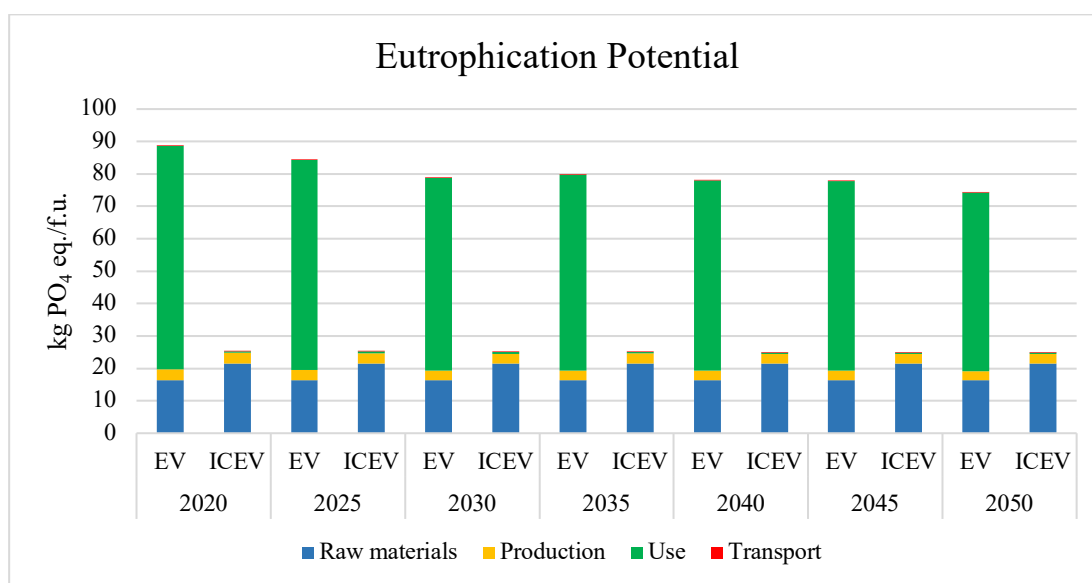


Figure 4.4: EP by years for both EV and ICEV.

4.2.4 Ozone layer depletion potential

The OLDP measured in kg CFC-11 eq./f.u. is illustrated in Figure 4.5, showing values for EVs and ICEVs over the same timeframe. Both vehicle types show a downward trend, indicating a reduction in ozone-depleting substances. EVs demonstrate a lower OLDP than ICEVs, particularly in the raw materials extraction phase. The values range from 0.007 to 0.008 kg CFC-11 eq./f.u for EVs, 0.008 to 0.009 kg CFC-11 eq./f.u for ICEVs. For EVs, a decreasing trend is observed in the OLDP of the use phase over the years. For both two vehicle types, OLDP is lower than other impacts.

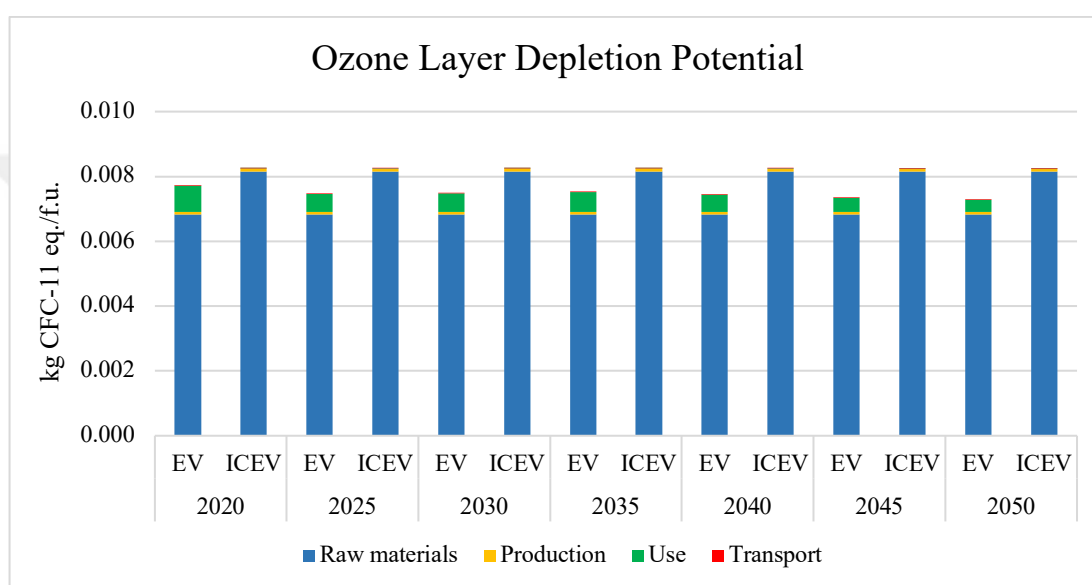


Figure 4.5: OLDP by years for both EV and ICEV.

4.2.5 Photochemical smog potential

Figure 4.6 presents the PSP measured in kg C₂H₄ eq./f.u. for both EVs and ICEVs by years. Both vehicle types exhibit a downward trend, reflecting a reduction in PSP over the years. EVs demonstrate significantly lower PSP values compared to ICEVs, particularly in the raw materials extraction phase. The PSP values for EVs range from 5.5 to 8 kg C₂H₄ eq./f.u., whereas for ICEVs, the values remain consistently around 11 kg C₂H₄ eq./f.u. indicating that the transition to EVs could significantly reduce air pollution and improve urban air quality. Additionally, a decreasing trend is observed in the PSP of the use phase for EVs over the years. Furthermore, while more than half of the total PSP for EVs originates from the use phase, the contribution of the use phase to the overall PSP of ICEVs is minimal. For ICEVs, the highest PSP is observed during the raw material extraction stage.

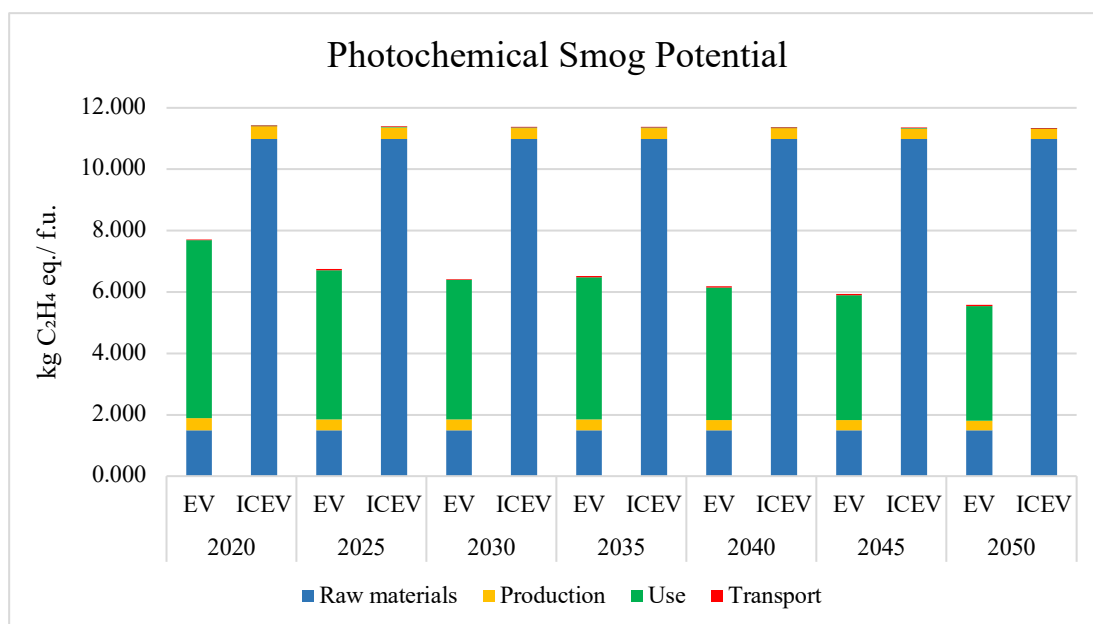


Figure 4.6: PSP by years for both EV and ICEV.

4.2.6 Human toxicity potential

The HTP is analyzed in Figure 4.7, showcasing how both EVs and ICEVs fare from 2020 to 2050. Over the years, a decreasing trend has been observed in the HTP during the use and production phases of EVs. This decline can be attributed to advancements in EV technology, improvements in energy efficiency, and the adoption of cleaner production methods. Notably, the use phase is the second-largest contributor to the total HTP for EVs, whereas its contribution to the overall HTP of ICEVs remains minimal. For both vehicle types, the raw material extraction stage is the dominant contributor to HTP. The HTP values range between 74,000 and 75,500 kg 1,4-DB eq./f.u. for EVs, while ICEVs consistently show a lower HTP of approximately 64,000 kg 1,4-DB eq./f.u. across all years. Despite the advancements in EVs technology, ICEVs maintain a comparatively lower HTP impact over the assessed years.

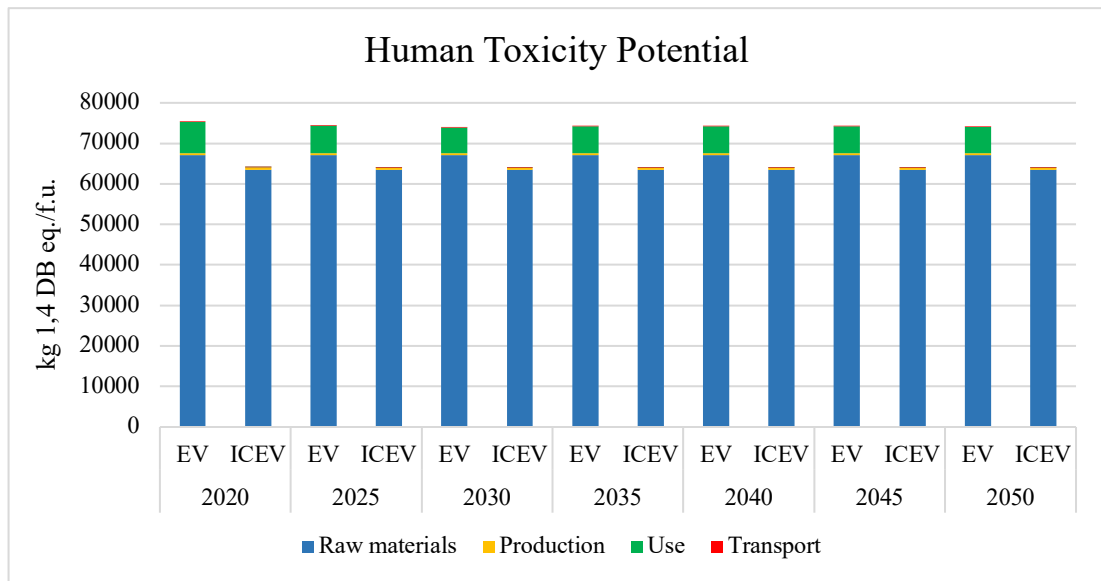


Figure 4.7: HTP by years for both EV and ICEV.

4.3 Normalization of the Results

Normalized values were found by dividing the LCA results obtained from the model by the values in Table 3.3 determined in the CML2001 method. Figure 4.8 shows the normalized impact results for all 6 impact categories. These results produce very similar results with the unnormalized ones. However, the difference in normalized values and the effects are in the order of 10^{-8} - 10^{-14} .

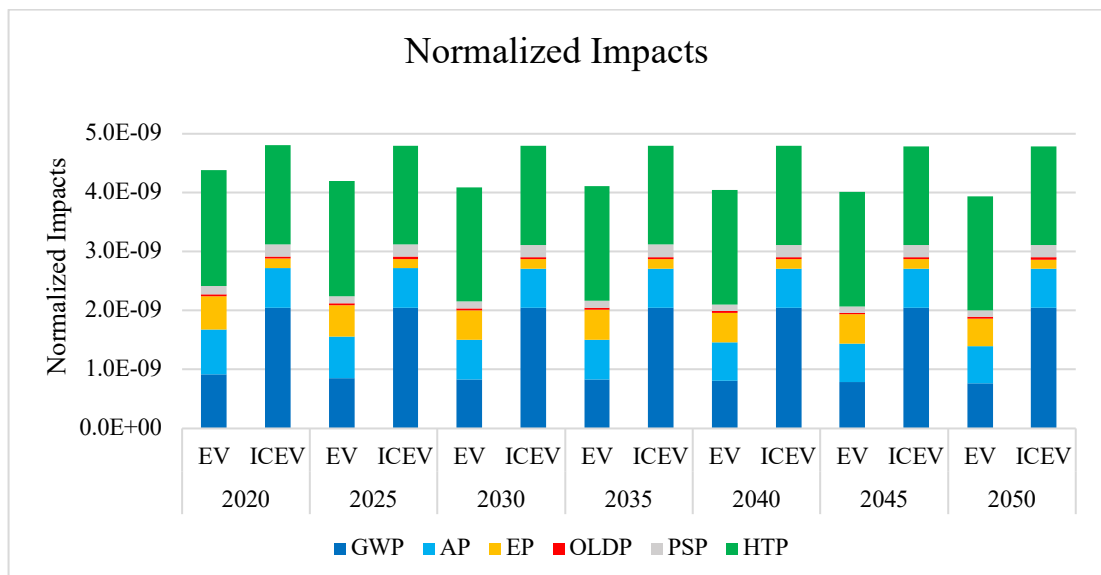


Figure 4.8: Normalized impact by years for EV and ICEV.

4.4 Survey Analysis

Figure 4.9, illustrates the distribution of respondents based on their years of experience in the profession: 39% have 0-5 years of experience with 21 participants, 7% have 6-10 years with 4 participants, 19% have 11-20 years with 10 participants, and 35% have more than 20 years with 19 participants. All participants work in the environmental sector. The distribution of respondents based on their years of professional experience provides a diverse range of insights, balancing the perspectives of both early-career and highly experienced professionals. This ensures that the survey results capture a broad spectrum of expertise, enriching the reliability and depth of the findings.

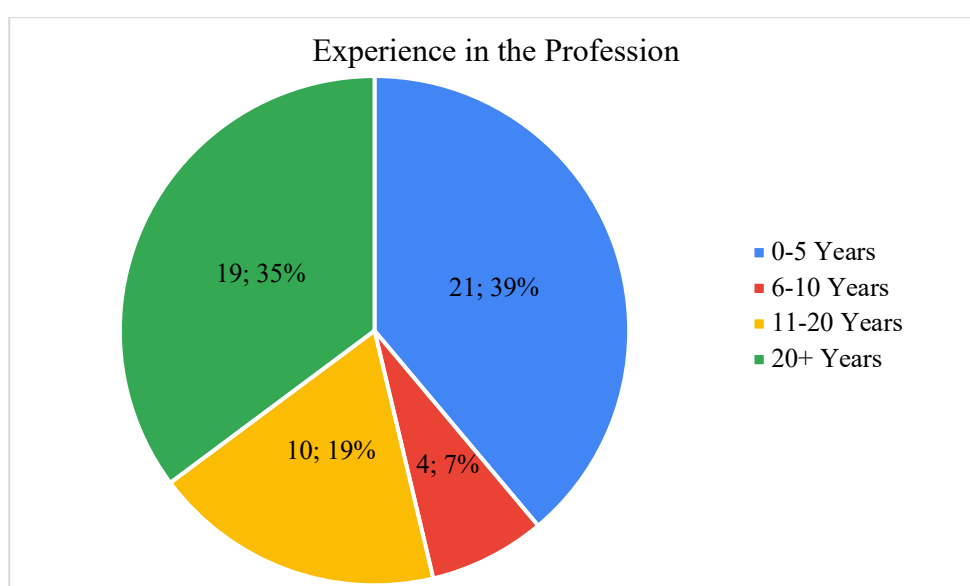


Figure 4.9: Experience year in the profession of survey participants.

Additionally, Figure 4.10 depicts vehicle ownership among respondents, showing that 28% do not own a vehicle with 15 people, while 72% do. Among vehicle owners, 64% own ICEVs with 34 people, 6% own HEVs with three people, and 2% own EVs with 1 person. This survey not only gathered insights from experts but also incorporated the perspectives of vehicle users and owners, ensuring a more comprehensive understanding of the subject matter.

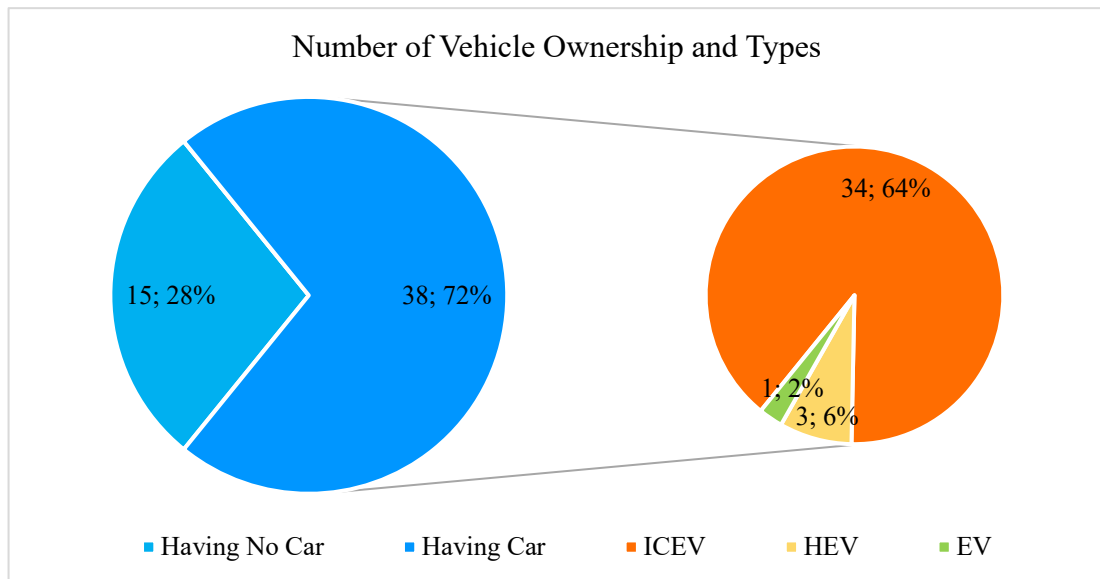


Figure 4.10: Number of vehicle ownership and types of survey participants.

Figure 4.11 shows that percentage of the survey participants who voted by weight. Figure 4.12 also presents that number of the survey participants who voted by weight. Among the six weights, GWP received the highest number of votes, with 36 participants (67%), while AP, EP, and OLDP each garnered the least votes, with only one participant. For the five-weight category, AP received the most votes, with 16 participants (30%), whereas EP received the least, with only two participants. Within the four-weight category, OLDP was the most favored, receiving 15 votes (28%), while GWP received the least, with only three participants. In the three-weight category, OLDP and PSP were equally prioritized, with 16 votes (30%) each, while GWP received no votes. For the two-weight category, AP was again the most selected, with 15 participants (28%), compared to GWP, which received only two votes. Finally, in the one-weight category, EP was the most frequently chosen, with 31 participants (57%), while OLDP received the least attention, with only two votes. These results highlight the varying importance participants placed on impact categories depending on the assigned weights.

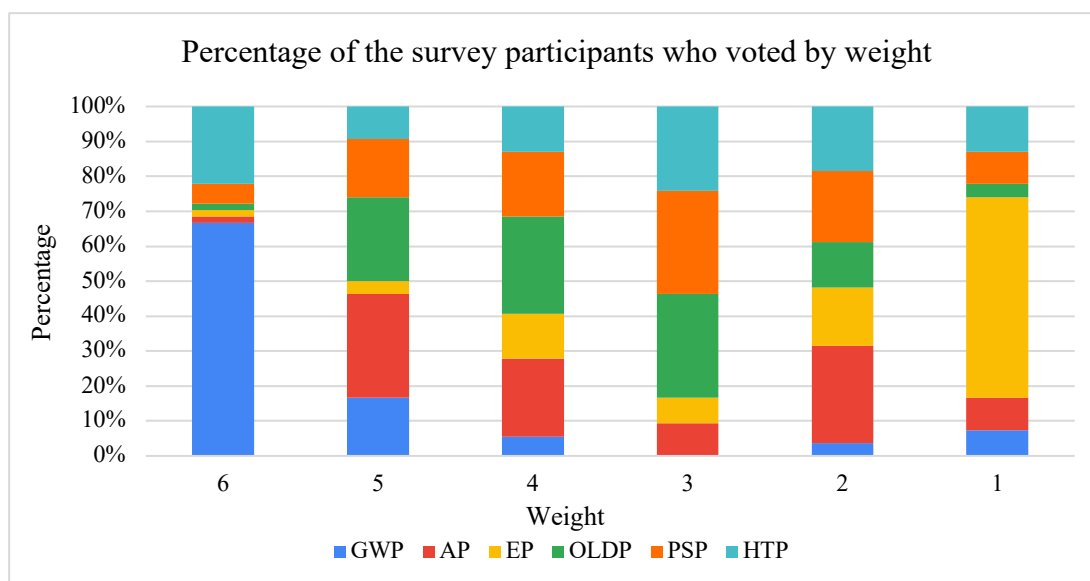


Figure 4.11: Percentage distribution of survey participants who voted according to weight values.

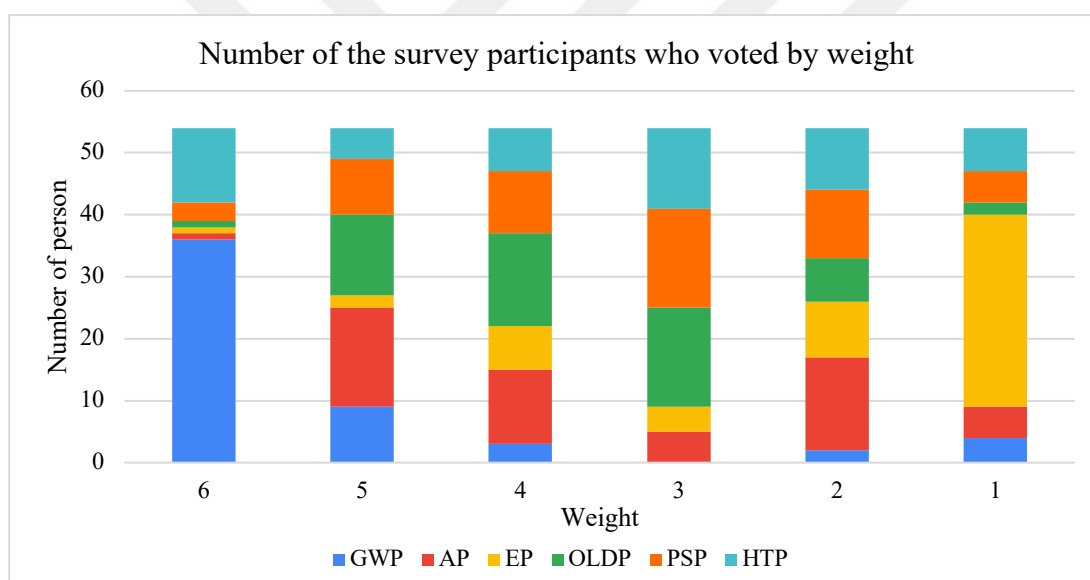


Figure 4.12: Number of survey participants who voted according to weight values.

Table 4.1 presents the coefficients of various environmental impact categories according to the votes given by the participants on the importance level as a result of the survey, including GWP at 0.25, AP at 0.16, EP at 0.09, OLDP at 0.17, PSP at 0.16, and HTP at 0.17.

Table 4.1: Weight coefficient by impact categories according to the survey.

Impact Category	Coefficient
GWP	0.25
AP	0.16
EP	0.09
OLDP	0.17
PSP	0.16
HTP	0.17

Figure 4.13 shows the overall normalized impacts for each year by comparing EVs and ICEVs according to the survey results. When considering the overall environmental impact, the EV consistently demonstrates a lower impact compared to the ICEV across all years. While the environmental impact of ICEVs shows a slight reduction over time, the decline is more pronounced for EVs, indicating a more significant improvement in their environmental performance over the assessed period. While the overall impact of ICEVs was 20% higher than that of EVs in 2020, this rate increased to 28% in 2050. This suggests that when environmental impacts are evaluated by weighting the various impact categories based on survey responses, EVs emerge as a more environmentally friendly alternative. The significant reductions in impacts especially GWP, EP, and PSP, especially in the use phase and raw material extraction, highlight the sustainability advantages of EVs over ICEVs. This trend is particularly evident as advancements in EV technology and cleaner electricity generation methods, including renewable energy sources in Türkiye's energy mix, contribute to decreasing environmental burdens year over year.

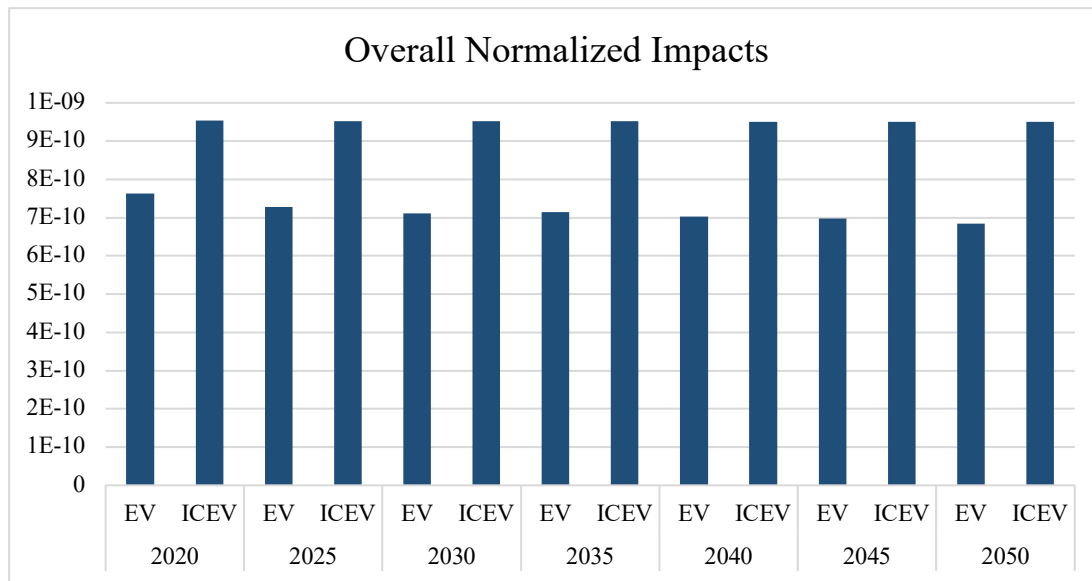


Figure 4.13: Overall normalized impacts for both EV and ICEV according to the survey results by years.

Table 4.2 presents the coefficients of various environmental impact categories according to equal importance level, including all six impact categories at 0.167.

Table 4.2: Equal weight coefficient by impact categories.

Impact Category	Coefficient
GWP	0.167
AP	0.167
EP	0.167
OLDP	0.167
PSP	0.167
HTP	0.167

Figure 4.14 shows the overall normalized impacts for each year by comparing EVs and ICEVs at equal coefficient situation. When considering the overall environmental impact, EVs consistently demonstrate a lower impact compared to ICEVs across all years, similar to the results observed in survey scenario. While the environmental impact of ICEVs shows a slight reduction over time, the decline is more pronounced for EVs, reflecting a more significant improvement in their environmental performance throughout the assessed period. In 2020, the overall impact of ICEVs was 8.7% higher than that of EVs; however, this difference increased to 17.7% by 2050. This suggests that when environmental impacts are evaluated by weighting the various impact categories based on equal coefficients, EVs again emerge as a more environmentally friendly alternative. Notably, in this scenario, the overall impact

difference between EVs and ICEVs is less pronounced than in the previous scenarios, highlighting the importance of considering weighted environmental impacts to better assess the sustainability of both vehicle types.

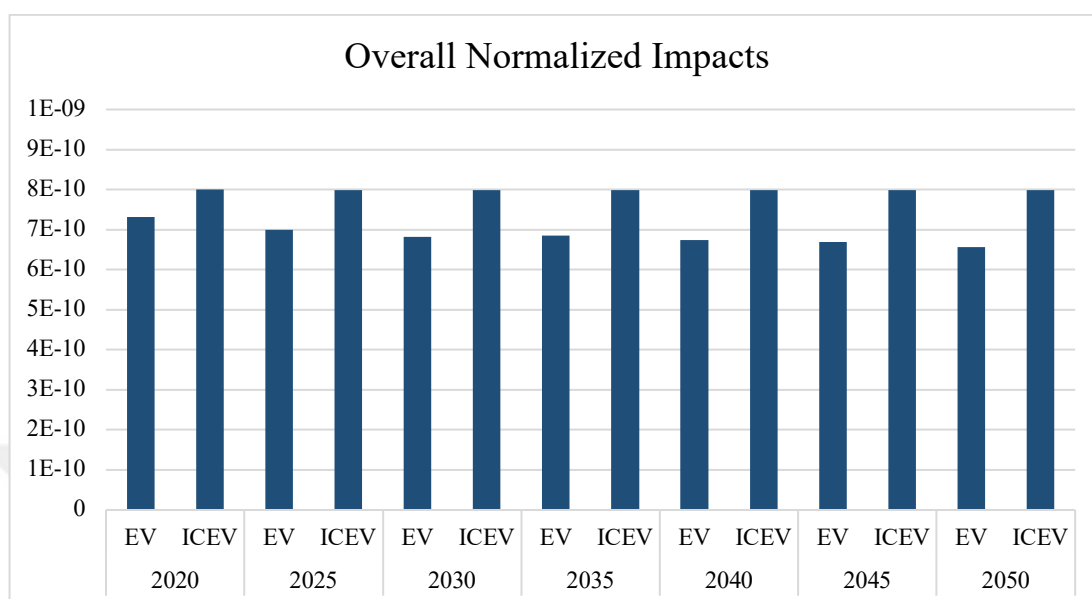


Figure 4.14: Overall normalized impacts for both EV and ICEV according to the equal weight coefficient by years.

The responses to the survey question about additional environmental impact factors highlighted several important points. A total of 54 participants provided answers, with common themes emerging. Resource depletion, particularly the use of abiotic resources like fossil fuels and minerals, was noted by 16 participants. Battery waste and recycling challenges were emphasized by 12 participants, while 7 mentioned the high water consumption and pollution associated with mining materials for EV batteries. 8 participants highlighted the noise pollution, and pointed out the environmental impacts of maintenance processes, such as tire changes, as well as end-of-life vehicle management. Other suggestions included ecotoxicity, particulate matter formation, and the energy mix used for electricity generation.

These responses contribute to the thesis by identifying additional impact categories, such as noise pollution and water footprint, that were not fully addressed in the study. They also highlight the need for future research to incorporate a broader range of factors in lifecycle assessments. This input enhances the study's comprehensiveness and offers valuable directions for future work and policy development.

4.5 Sensitivity Analysis

In the context of this thesis, the findings reveal that the raw material and usage stages contribute the highest shares, almost all, across all six impact categories analyzed. Considering the significant influence of these stages on the overall LCA, a detailed sensitivity analysis has been planned. Sensitivity analysis, a method used to evaluate how changes in input variables affect the outcomes of a model, will be conducted to assess the potential variations in the results due to uncertainties or changes in key parameters.

Specifically, this analysis will focus on the raw material production and usage stages for both vehicle types, for 2020 and 2050. The objective is to examine the impact of these stages under varying conditions and to determine their relative contributions to the life cycle environmental impacts. By incorporating this analysis, the study aims to enhance the stability of the results and provide deeper insights into the critical factors driving the environmental performance of EVs and ICEVs over time. Sensitivity analysis was conducted to evaluate how variations in critical parameters, such as lifetime extension and sets of tire usage impact environmental indicators. Sensitivity analysis is a systematic approach to determining how changes in input variables influence the results of a model.

The sensitivity analysis was performed for three scenarios:

- Base Scenario: Default lifetime assumptions (EV: 15 years and 5 sets of tire, ICEV: 20 years, 6 sets of tire).
- Life Time Extension Scenario: Extended lifetimes (EV: 20 years and 5 sets tires, ICEV: 25 years and 6 sets tires), resulting in increased higher energy consumption (electricity for EVs and gasoline for ICEVs).
- Tire Scenario: Extended tire sets (EV: 15 years and 6 sets of tire, ICEV: 20 years and 7 sets of tire), resulting in increased material usage (e.g., one additional set of tires).

To quantify the relative change in environmental impacts, the following formula was applied for two modified scenario (4.1):

$$Relative\ Change\ (\%) = \frac{Modified\ Scenario - Base\ Scenario}{Base\ Scenario} \times 100 \quad (4.1)$$

Additionally, the sensitivity coefficient was calculated to measure the degree of sensitivity of each impact category to the changes in the variables (4.2):

$$\text{Sensitivity Coefficient} = \frac{\text{Change in Impact (\%)}}{\text{Change in Assumptions (\%)}} \times 100 \quad (4.2)$$

The analysis revealed significant variations in environmental impacts due to lifetime extension and increased tire usage. As the sensitivity analysis revealed changes only in the raw materials and use stages, and these changes were observed exclusively in the GWP impact category, only the results reflecting these variations have been presented. Figure 4.15 summarizes the sensitivity coefficient observed in the GWP for both vehicle types in 2020 and 2050. As illustrated in the graph, in the scenario where the vehicle lifetime is extended, changes were observed exclusively in the use stage for EVs since only electricity consumption increased. In 2020, sensitivity coefficient is higher than 2050 for EV. Because, non-renewable energy usage is higher than 2050. For ICEVs, changes were also observed in the use stage, as the impact of gasoline is reflected in the raw materials phase. Additionally, it is evident that the changes within the stages are higher compared to the changes in the total impact when the vehicle lifetime is extended. The most significant change for EVs occurred in the use stage (~95%), while for ICEVs the largest change was also in the use stage (~35%). The change in EVs was more than twice the change in ICEVs. In addition, the scenario where the number of sets of tires is extended, the change occurred only at the raw material stage for both vehicle types. The sensitivity coefficient is equal in both years for each vehicle type.

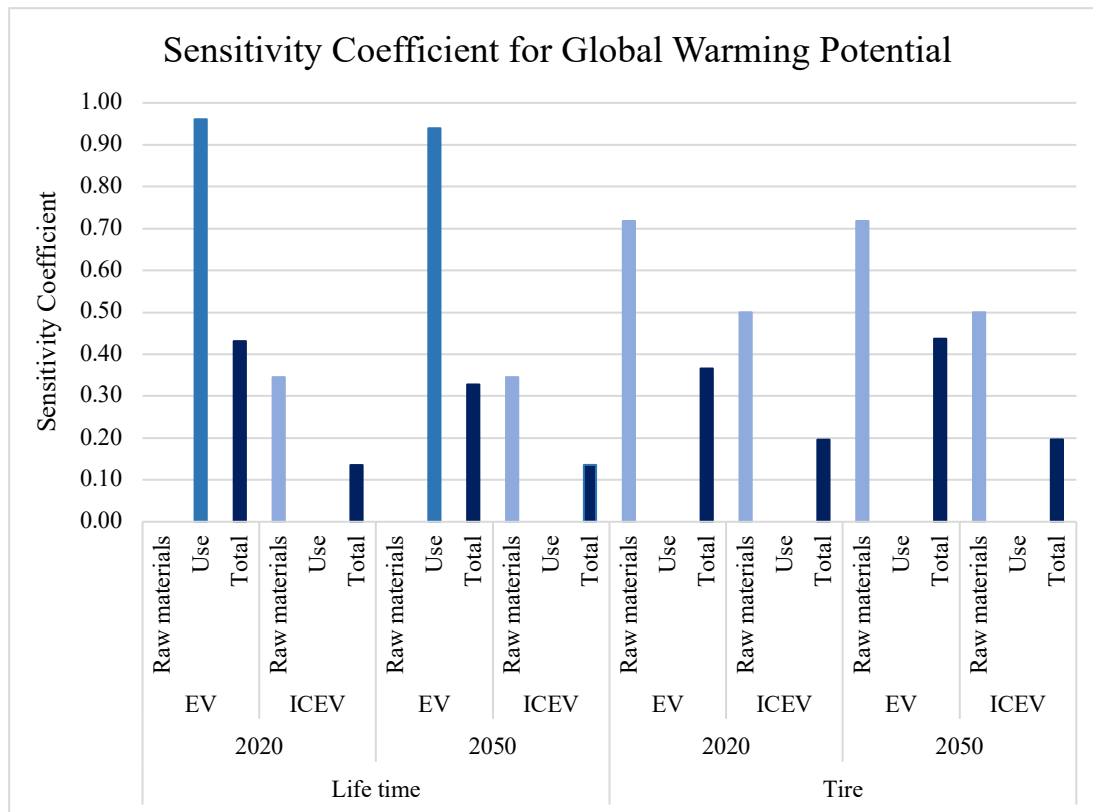


Figure 4.15: Sensitivity coefficient for two scenarios in 2020 and 2050.

4.6 Interpretation of Results

In the context of sensitivity analysis, interpretation refers to analyzing and understanding the outcomes of the analysis to identify which input variables have the most significant impact on the model's results. It involves evaluating the magnitude and direction of changes in environmental impacts (or other outcomes) in response to adjustments in key variables including:

- **Magnitude of Change:** Determining how much the results vary when input parameters are modified.
- **Significance of Variables:** Identifying which parameters (e.g., energy consumption, material usage) are most influential in driving the observed changes.
- **Phase-Specific Insights:** Understanding which life cycle phases (e.g., raw material, use phase) are the most sensitive to the changes.
- **Actionable Insights:** Translating findings into strategies for improving system performance or minimizing negative impacts.

In sensitivity analysis, effective interpretation helps prioritize efforts to address the most critical factors influencing the results.

The use phase exhibited the highest relative change in GWP for both EVs and ICEVs, primarily due to increased energy consumption (electricity for EVs and gasoline for ICEVs) associated with lifetime extension. This highlights the critical role of energy efficiency in minimizing environmental impacts. Although the raw material phase showed a lower relative change compared to the use phase, the addition of one set of tires had a noticeable impact, particularly for EVs. The sensitivity coefficient for the use phase was significantly higher than that of the raw material phase, emphasizing the importance of targeting energy consumption reductions to achieve substantial environmental benefits.

The sensitivity analysis demonstrates that extending the lifetime of vehicles significantly impacts environmental indicators, especially through increased energy consumption in the use phase. These findings underscore the need for sustainable energy solutions and material efficiency to minimize the environmental footprint of both EVs and ICEVs.

4.7 Comparison of Results with Literature Values

To compare the environmental impacts of EVs in Türkiye with those produced abroad, similar international studies were reviewed, and the data presented in Table 4.3 was compiled. It is important to note that for meaningful comparisons, the functional units of the studies must either be defined in the same way or easily convertible. A review of the literature indicates that the results obtained in this study align closely with those reported internationally, validating the methodology and assumptions employed. Also, system boundaries of the studies were given in the Table 4.3. For instance, the average GWP values calculated in referenced studies were 0.28 kg CO₂-eq for EVs and 0.36 kg CO₂-eq for ICEVs. In this study for Türkiye, these values were calculated as 0.12 kg CO₂-eq and 0.21 kg CO₂-eq, respectively.

As can be seen from Table 4.3, the values are variable. The reason for this is thought to be factors such as system boundaries being different, electricity generation being obtained from different sources, and distance to raw materials, as stated in the Table 4.3. When comparing the environmental impacts of other countries with Türkiye, it is

evident that most countries demonstrate lower impact values. This difference is not primarily due to the production or operation of EVs or ICEVs but rather to the environmental characteristics of electricity generation in these countries. Similar to Türkiye, Poland relies heavily on fossil fuels for electricity generation, resulting in higher environmental impact values (Burchart-Korol, et al., 2018). On the other hand, according to the study conducted for India, these values are very high (Das, 2022). The reason for this is that the electricity mix in India is thought to be provided mostly from non-renewable resources. This underscores the critical importance of reducing the share of fossil fuels in Türkiye's electricity mix and increasing the contribution of renewable energy. Such a shift is essential to lowering the country's CF and overall environmental impacts, particularly as EV adoption continues to rise.



Table 4.3: Comparison of the results against the literature.

Country	System boundaries	Vehicle Type	GWP (kgCO ₂ eq)	AP (gSO ₂ eq)	EP (10×gPO ₄ eq)	OLDP (kgCFC-11eq)	PSP (10×gC ₂ H ₄ eq)	HTP (kg1,4 DB eq)
This study	Cradle-to-grave ⁿ	EV	0.13	0.61	2.96	2.58	0.26	0.25
		ICEV	0.21	0.40	0.63	2.06	0.29	0.16
Türkiye ^a	Cradle-to-grave	EV	0.12	3.21	0.83	2.76	0.26	0.25
		ICEV	0.21	0.48	0.58	2.07	0.29	0.16
Italy ^{b,c}	Cradle-to-grave	EV	0.13	-	-	-	-	0.03
		ICEV	0.203	-	-	-	-	0.00
Brazil ^d	Cradle-to-grave	EV	0.16	0.24	0.36	1.0	0.225	0.0375
		ICEV	0.27	0.25	0.50	1.70	0.6	0.016
Poland ^e	Cradle-to-grave	EV	0.276	1.56	3.26	-	-	0.33
		ICEV	0.284	0.71	0.53	-	-	0.085
Czech Rep. ^e	Wheel-to-wheel	EV	0.214	0.85	3.07	-	-	0.31
		ICEV	0.284	0.71	0.53	-	-	0.27
Spain ^f	Cradle-to-grave	EV	0.12	-	-	-	-	-
		ICEV	0.25	-	-	-	-	-
Lithuania ^g	Cradle-to-grave	EV	0.142	-	-	-	-	0.077
		ICEV	0.105	-	-	-	-	0.009
Sweden ^h	Wheel-to-wheel	EV	-	-	-	-	-	0.46
		ICEV	-	-	-	-	-	0.27
Canada ⁱ	Well-to-wheel	EV	0.16	-	-	-	-	0.26
		ICEV	0.27	-	-	-	-	0.03
India ^j	Cradle-to-grave	EV	0.343	-	-	-	-	-
		ICEV	0.255	-	-	-	-	-
Switzerland ^k	Wheel-to-wheel	EV	0.22	-	-	-	-	1.00
		ICEV	0.3	-	-	-	-	0.26
China ^l	Cradle-to-grave	EV	0.209	-	-	-	-	-
		ICEV	0.233	-	-	-	-	-
Norway ^m	Cradle-to-grave	EV	0.61–1	-	-	-	-	0.7–1
		ICEV	0.81	-	-	-	-	0.25

a: (Üçtuğ, 2022); *b:* (Pero, et al., 2018); *c:* (Girardi, et al., 2015); *d:* (de Souza, et al., 2018); *e:* (Burchart-Korol, et al., 2018); *f:* (Puig-Samper Naranjo, et al., 2021); *g:* (Petrauskienė, et al., 2019); *h:* (Nordelöf, et al., 2014); *i:* (Bicer & Dincer, 2018); *j:* (Das, 2022); *k:* (Bauer, et al., 2015); *l:* (Wu, et al., 2018); *m:* (Hawkins, et al., 2012); *n:* (Results of 2020 data).



5. CONCLUSION

The transition to EVs represents a pivotal development in addressing global challenges such as climate change, energy security, and urban air quality. This study has assessed the life cycle environmental impacts of EVs compared to ICEVs, utilizing a detailed projection of Türkiye's electricity generation mix from 2020 to 2050. The findings provide critical insights into the evolving environmental footprint of EVs as the energy sector transitions toward renewable and low-carbon sources.

The results underscore the importance of the electricity generation mix in determining the life cycle performance of EVs. As Türkiye's electricity grid incorporates higher shares of renewable energy, environmental impacts of EVs is projected to decrease significantly. By 2050, with a predominantly renewable grid, EVs are expected to exhibit moderately lower impact compared to ICEVs.

While EVs demonstrate advantages in terms of tailpipe emissions, their manufacturing phase, particularly the production of lithium-ion batteries, remains energy-intensive. Recycling and second-life applications for EV batteries can substantially mitigate these impacts, emphasizing the need for improved waste management strategies and advancements in battery technology.

The study's projections are based on the assumption that Türkiye will continue to increase its share of renewable energy in electricity generation. However, if this transition does not proceed as expected -due to policy changes, economic constraints, or technological barriers- the environmental benefits of EVs could be substantially diminished. A grid dominated by fossil fuels would exacerbate the CF of EVs, making them less environmentally favorable compared to ICEVs. Sensitivity analyses highlight the critical importance of decarbonizing the energy sector to maximize the sustainability benefits of EV adoption.

Despite the environmental advantages of EVs, several practical challenges remain, particularly in the context of Türkiye. The country's current EV infrastructure is insufficient to support a large-scale transition. Expanding the network of charging

stations and ensuring compatibility with various EV models will require significant investments. Additionally, the costs associated with upgrading electricity grids to accommodate increased demand must be considered. Furthermore, EVs face operational limitations that could hinder their widespread adoption. These include longer charging times, shorter driving ranges compared to ICEVs, and the risk of battery-related incidents such as fires or explosions. Addressing these issues will be crucial to enhancing the reliability and safety of EVs while reducing public concerns.

Despite these challenges, EVs currently present a more environmentally sustainable alternative to ICEVs. The analysis shows that EVs have a lower GWP, particularly as the share of renewable energy in electricity generation increases. While EVs exhibit higher impacts during the production phase -mainly due to battery manufacturing- these are offset by their superior performance during the use phase. In addition, EVs have the potential to reduce urban air pollution and improve public health by eliminating tailpipe emissions.

Through expert-weighted analysis, this study harmonized six distinct environmental impact categories into a single metric. This approach provides a comprehensive understanding of the trade-offs between various environmental impacts, aiding policymakers and stakeholders in making balanced decisions.

The temporal analysis highlights a critical dependency on policy interventions to accelerate the decarbonization of the energy sector. Policy measures such as subsidies for renewable energy, stricter vehicle emissions standards, and incentives for EV adoption are essential for realizing the environmental benefits of electric mobility.

This thesis contributes to the body of knowledge by integrating a forward-looking perspective into LCA studies. Unlike static assessments, the inclusion of temporal changes in the energy grid provides a realistic depiction of future environmental scenarios. The methodology developed for aggregating multi-dimensional impact factors offers a replicable framework for similar studies globally.

Although this study offers valuable insights, there are certain limitations that call for further exploration. The projections rely on assumptions about future energy policies and technological advancements, which may deviate from actual developments. Additionally, the study primarily focuses on the environmental impacts within Türkiye, limiting its generalizability to regions with different energy profiles.

Future research could expand on this work by exploring the socio-economic impacts of EV adoption, investigating the integration of EVs with smart grids and renewable energy storage systems, and conducting real-world assessments of battery recycling and reuse pathways. Additional impact categories such as noise pollution and resource depletion can be included to examine and compare the impacts. In addition, in further studies, the survey conducted in this study can be expanded to include social LCA.

This study highlights the need for a comprehensive perspective when assessing the environmental impacts of EVs and ICEVs. While EVs clearly have environmental benefits, fully unlocking their potential depends on overcoming infrastructure challenges, advancing battery technology, and accelerating the shift to renewable energy. Collaboration among policymakers, industry leaders, and researchers is essential to develop strategies that not only encourage EV adoption but also address the economic, social, and environmental hurdles that come with it. With these efforts, Türkiye can make meaningful progress toward a cleaner, more sustainable future in transportation.



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APPENDICES

APPENDIX A: Supplementary Data



APPENDIX A

Table A. 1: Energy supply (ktoe) by sources.

Energy supply (ktoe)	Coal	Oil	Gas	Electricity	Nuclear	Biomass	Hydro electric	Wind	PV
2020	9837	246	6838	148	0	1122	6715	2135	938
2025	10526	226	5293	160	0	1259	9907	5578	1594
2030	12446	109	7296	199	33	2067	11490	6613	4743
2035	16818	100	10211	214	220	497	12210	9520	9395
2040	19533	112	9965	176	590	95	12605	13558	15844
2045	21967	98	8114	184	1171	87	13146	16430	21496
2050	21872	86	6542	222	1511	83	13616	17086	27810

Table A. 2: Environmental impacts of the electricity sources.

Environmental Impact Categories/Electricity Sources	Lignite	Hard Coal	Gas	Large Reservoir	Small Reservoir	Run-off River	Wind	Geothermal
AP (g SO ₂ eq)	10.8	6	0.8	0.03	0.07	0.15	0.31	87.55
EP (g PO ₄ eq)	11.9	2.3	0.1	0.12	0.28	0.63	1.52	0.1
GWP (0.1 kg CO ₂ eq)	10.6	11.3	5	0.83	0.42	0.41	0.73	6.3
HTP (0.1 kg DB eq)	13.9	3	0.06	0.02	0.05	0.07	0.21	0.01
OLDP (0.01 mg R11 eq)	0.2	0.8	9.2	0.06	0.11	0.25	0.4	-0.000004
PSP (0.1 g C ₂ H ₄ eq)	4.8	3.3	1.8	0.21	0.12	0.21	0.41	0.12

Table A. 3: EV life cycle inventory.

Input (Output)	Unit	Amount	Ecoinvent Process
PRODUCTION			
Aluminum	kg	74.4 ^a	Aluminum (rolled, virgin)
Aluminum (recycled)	kg	5.6 ^a	Aluminum (rolled, 48% recycled)
Vehicle Tires	pcs	20 ^b	(Process generated by the user)
Lithium Ion Battery	pcs	1 ^a	Battery, Lilo, rechargeable, prismatic, at plant
Iron	kg	25 ^a	Cast iron, at plant
Steel	kg	857 ^a	Chromium steel 18/8, at plant
Copper	kg	59 ^a	Copper sheet
Glass	kg	44 ^a	Flat glass, coated, at plant
Lead Acid Battery	pcs	1 ^c	(Process generated by the user)
Lubricating Oil	kg	26 ^a	Lubricating oil, at plant
Polypropylene	kg	120 ^a	Polypropylene fibers
PVC	kg	30 ^a	PVC calendered sheet
Synthetic Rubber	kg	22 ^a	Synthetic rubber, at plant
Electrical Energy	MJ	4089 ^d	(Process generated by the user)
Heat Energy (Coal)	MJ	3705 ^a	Heat, at hard coal industrial furnace 1-10 MW
Heat Energy (Natural Gas)	MJ	5688 ^a	Heat, natural gas, at industrial furnace, > 100 kW
TRANSPORTATION			
Lithium Ion Battery Import (from China to Gebze)	km	17,000	
Car Delivery from Factory to Sales Point	km	200	
USE			
Electric Energy	GJ	108	(Process generated by the user)
DISPOSAL			
<i>Aluminum Disposal</i>	kg	74.4 ^a	Disposal, aluminum, 0% water, to sanitary landfill
<i>Steel Recycling</i>	kg	58 ^a	Disposal, building, reinforcement steel, to recycling
<i>Rubber Disposal</i>	kg	202* ^a	Disposal, rubber, unspecified, 0% water, to municipal incineration
<i>Metal Disposal</i>	kg	847 ^a	Landfill – ferro metals
<i>Glass Disposal</i>	kg	44 ^a	Landfill – glass/inert matter
<i>Plastic Disposal</i>	kg	140 ^a	Landfill – plastic
<i>Plastic Recycling</i>	kg	11 ^a	Recycling, PE
<i>Battery Disposal</i>	kg	300** ^a	Shredding, electrical and electronic scrap

(*) The rubber disposed includes automobile tires, so the quantities of rubber entering and exiting the system may not match.

(**) The battery was initially entered as a unit; later its mass equivalent was calculated, and disposal was modeled based on this value (Premrudee, et al., 2013).

(^a) (Yang, et al., 2021)

(^b) (Dong, et al., 2021)

(^c) (Premrudee, et al., 2013)

(^d) (Atilgan & Azapagic, 2016 (b))

Note: In the table, system inputs are shown in regular font, while outputs are indicated in italicized font.

Table A. 4: ICEVs life cycle inventory.

Input (Output)	Unit	Amount	Ecoinvent Process
PRODUCTION			
Aluminum	kg	81 ^a	Aluminium (rolled, virgin)
Aluminum (recycled)	kg	6 ^a	Aluminium (rolled, 48% recycled)
Vehicle Tire	unit	24 ^b	User-defined process
Iron	kg	139 ^a	Cast iron, at plant
Steel	kg	793 ^a	Chromium steel 18/8, at plant
Copper	kg	24 ^a	Copper sheet
Glass	kg	37 ^a	Flat glass, coated, at plant
Lead-Acid Battery	unit	1 ^c	User-defined process
Motor Oil	kg	26 ^a	Lubricating oil, at plant
Polypropylene	kg	112 ^a	Polypropylene fibers
Polyvinyl Chloride	kg	29 ^a	PVC calendered sheet
Rubber	kg	29 ^a	Synthetic rubber, at plant
Electricity	MJ	4180 ^d	User-defined process
Thermal Energy (Coal)	MJ	3788 ^a	Heat, hard coal industrial furnace, 1-10 MW
Thermal Energy (Natural Gas)	MJ	5816 ^a	Heat, natural gas, industrial furnace, >100 kW
TRANSPORTATION			
Factory to Sales Point	km	200	Transport, lorry >28t, fleet average
USE			
Gasoline	kg	16,600 ^a	Gasoline
<i>Benzene Emissions</i>	kg	69.7 ^a	Benzene emissions to air
<i>Carbon Dioxide Emissions</i>	kg	49,700 ^a	CO ₂ emissions to air
<i>Nitrogen Oxides Emissions</i>	kg	15.9 ^a	NO ₂ emissions to air
<i>Sulfur Dioxide Emissions</i>	kg	19.8 ^a	SO ₂ emissions to air
DISPOSAL			
<i>Aluminum Disposal</i>	kg	81 ^a	Disposal, aluminum, 0% water, to landfill
<i>Steel Recycling</i>	kg	55.5 ^a	Disposal, reinforcement steel, to recycling
<i>Rubber Disposal</i>	kg	245(*) ^a	Disposal, rubber, to municipal incineration
<i>Metal Disposal</i>	kg	900 ^a	Landfill, ferro metals
<i>Glass Disposal</i>	kg	37 ^a	Landfill, glass/inert matter
<i>Plastic Disposal</i>	kg	131 ^a	Landfill, plastic
<i>Plastic Recycling</i>	kg	10 ^a	Recycling, PE

(*) Since automobile tires are included in the amount of rubber disposed of, the input and output quantities of rubber in the system do not match.

(**) The battery was initially entered into the system as a unit, but its mass equivalent was later calculated, and disposal was modeled based on this value (Premrudee, et al., 2013).

(^a) (Yang, et al., 2021)

(^b) (Dong, et al., 2021)

(^c) (Premrudee, et al., 2013)

(^d) (Atilgan & Azapagic, 2016 (b))

Note: In the tables, system inputs are shown in regular font, while outputs are indicated in italicized font.

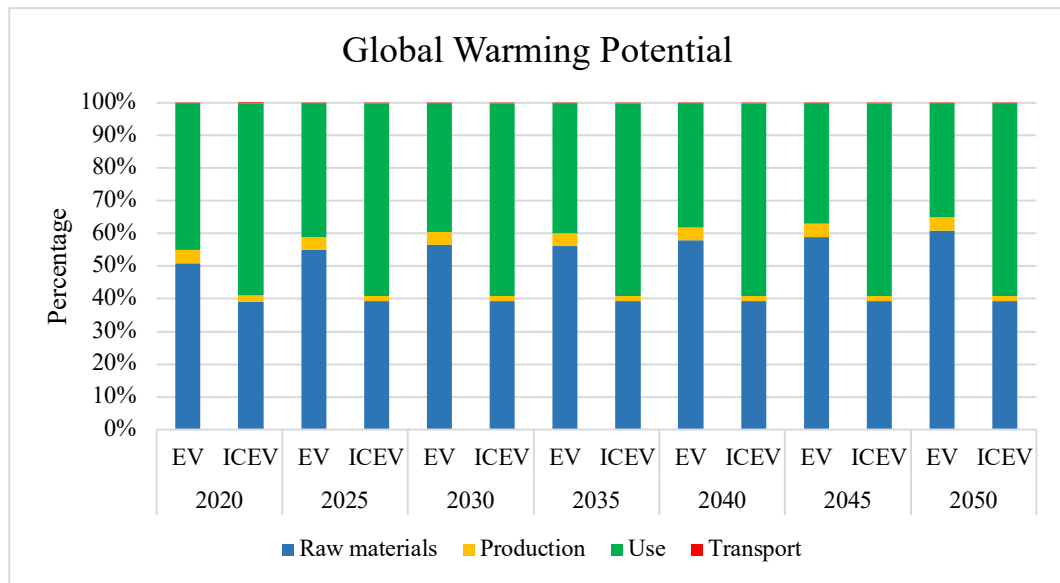


Figure A. 1: GWP percentage of each stage for EVs and ICEVs by years.

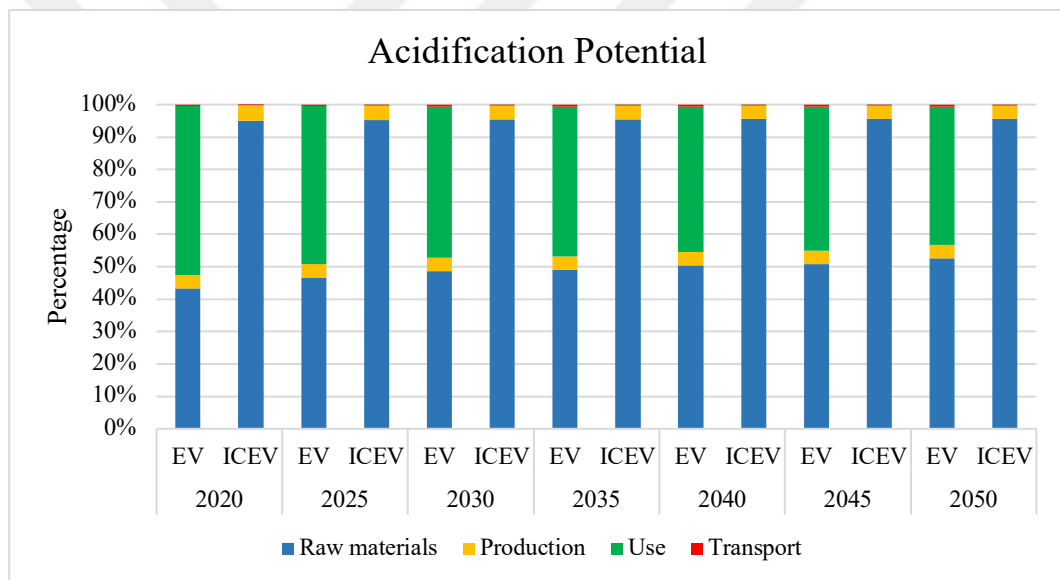


Figure A. 2: AP percentage of each stage for EVs and ICEVs by years.

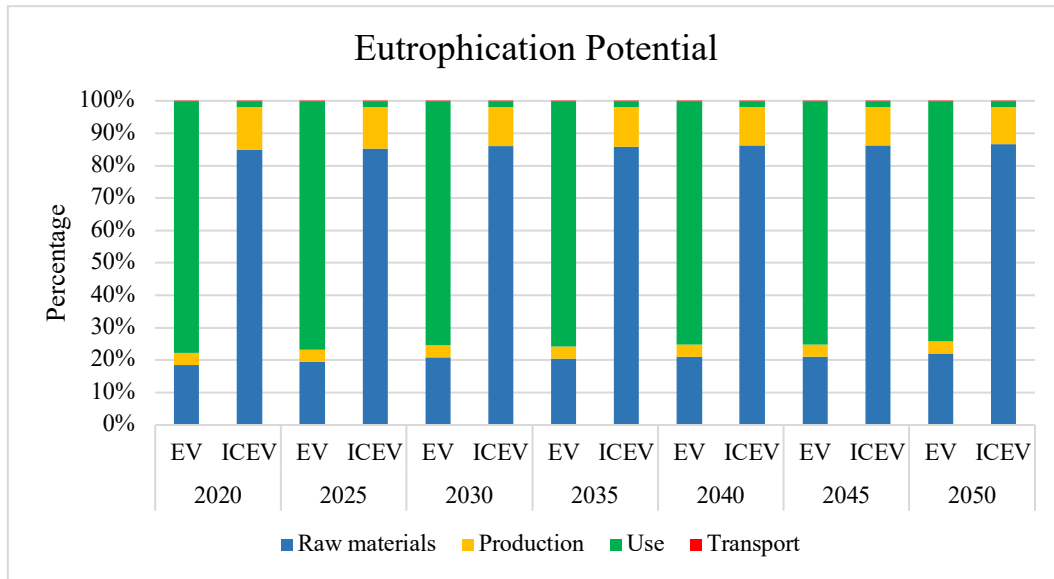


Figure A. 3: EP percentage of each stage for EVs and ICEVs by years.

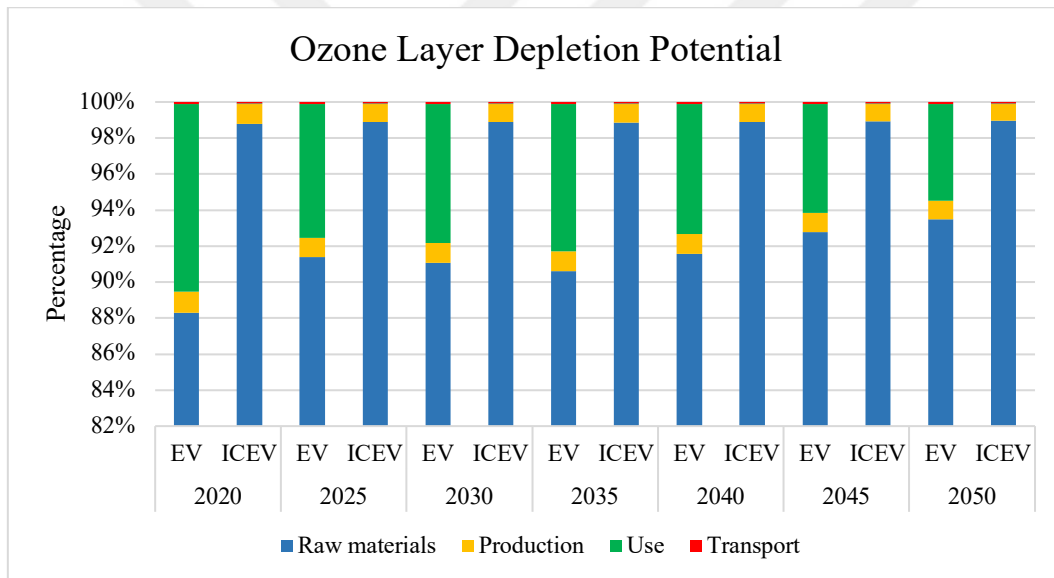


Figure A. 4: OLDP percentage of each stage for EVs and ICEVs by years.

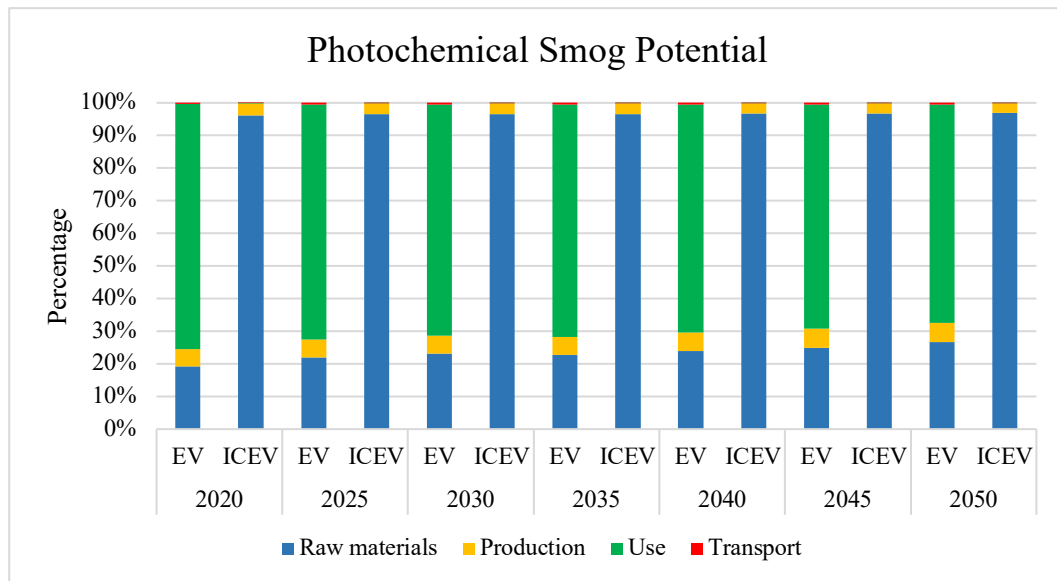


Figure A. 5: PSP percentage of each stage for EVs and ICEVs by years.

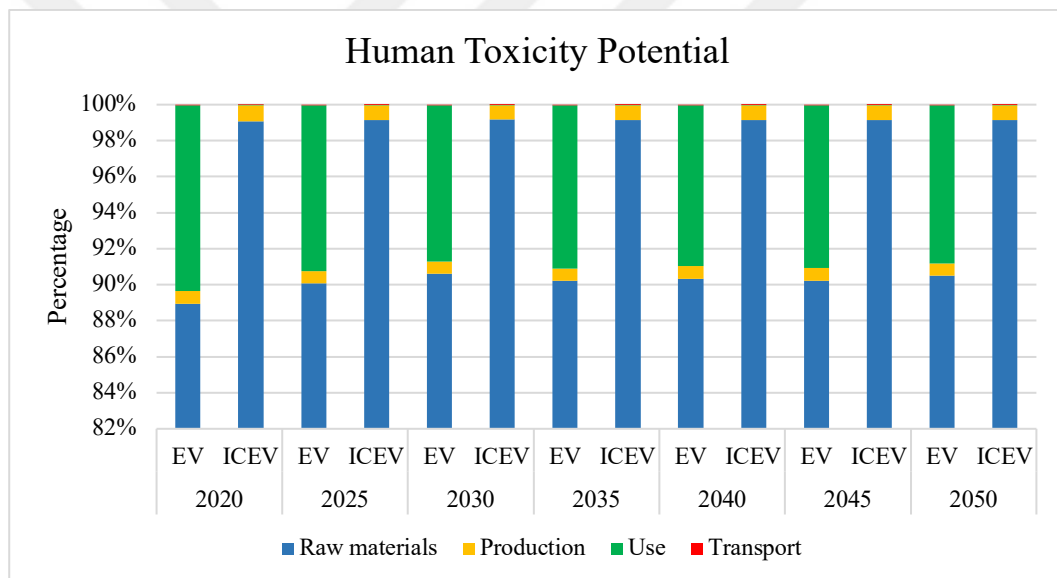


Figure A. 6: HTP percentage of each stage for EVs and ICEVs by years.



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