

A COMPARATIVE LIFE CYCLE ASSESSMENT OF
MAGNESIUM AND ALUMINUM TRANSMISSION
SYSTEM

BY

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A dissertation submitted in fulfillment of the requirement for
the Degree of Master of Science in Mechanical Engineering.

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ABSTRACT

This study assesses the life-cycle environmental impacts of magnesium (Mg) and aluminum (Alu) in automotive transmission systems, with emphasis on energy consumption, greenhouse gas (GHG) emissions, and trade-offs between production and use phases. The study employs Life Cycle Assessment (LCA) based on ISO 14040/14044 standards and iterative analysis through the GREET model covering material extraction, production processes, use phase and end-of-life processes. Results show that due to its lightweight property, Mg provides a significant benefit during the use phase, with total energy consumption for Mg transmissions being 16.6–17.4% lower than for Alu systems. The emissions in the use phase of Mg are also lower, with a decrease in CO₂ emissions of 23.6%, compensating for its higher production-phase emissions. Mg shows better performances in some emissions categories, such as a 74% reduction in SO_x emissions compared to Alu. While the GHG emissions during production of Mg are higher, advancements in Mg manufacturing technologies such as cleaner electrolytic processes and alternative cover gases may reduce the environmental impact in the future. The results highlight Mg's potential to replace Alu as the primary material in automotive transmission systems, especially as production advances continue to improve. Based on Mg's higher use-phase performance and the continuous development of Mg technologies, the results of the study confirm that, compared to Alu, Mg can be considered as a promising and sustainable alternative, which may lead to Mg potential becoming one of the primary materials across multiple sectors within the next decade.

ملخص البحث

تُقيّم هذه الدراسة التأثيرات البيئية عند استخدام المغنيسيوم (Mg) والألمنيوم (Al) في أنظمة نقل الحركة في السيارات، مع التركيز على استهلاك الطاقة، وانبعاثات الغازات المسببة للاحتباس الحراري (GHG)، والمفاضلات بين مرحلتي الإنتاج والاستخدام. تعتمد الدراسة على تقييم دورة الحياة (LCA) وفقاً لمعايير ISO 14040/14044، وتحليل تكراري باستخدام نموذج GREET الذي يغطي استخراج المواد، وعمليات الإنتاج، ومرحلة الاستخدام، وعمليات نهاية العمر الافتراضي للمادة. تُظهر النتائج أن المغنيسيوم، بفضل خفة وزنه، يوفر فائدة كبيرة خلال مرحلة الاستخدام، حيث يكون إجمالي استهلاك الطاقة في أنظمة النقل المصنوعة من المغنيسيوم أقل بنسبة تتراوح بين 16.6% و 17.4% مقارنةً بأنظمة الألمنيوم. كما أن انبعاثات ثاني أكسيد الكربون (CO₂) في مرحلة الاستخدام أقل بنسبة 23.6%، مما يعوض عن الانبعاثات الأعلى في مرحلة الإنتاج. ويُظهر المغنيسيوم أداءً أفضل في بعض أنواع الانبعاثات، مثل تقليل انبعاثات ثاني أكسيد الكبريت (SO_x) بنسبة 74% مقارنةً بالألمنيوم. وعلى الرغم من أن انبعاثات الغازات المسببة للاحتباس الحراري أثناء إنتاج المغنيسيوم أعلى، فإن التقدم في تقنيات تصنيع المغنيسيوم، مثل العمليات التحليلية الكهربائية والغازات البديلة، قد يقلل من الأثر البيئي في المستقبل. وتسلط النتائج الضوء على إمكانية أن يحل المغنيسيوم محل الألمنيوم كمادة أساسية في أنظمة نقل الحركة في السيارات، خاصة مع استمرار التقدم في تقنيات الإنتاج. وبناءً على الأداء الأفضل للمغنيسيوم في مرحلة الاستخدام والتطور المستمر في تقنياته، تؤكد نتائج الدراسة أن المغنيسيوم يمكن اعتباره بديلاً واعدًا ومستدامًا مقارنةً بالألمنيوم، وقد يصبح من المواد الأساسية في

عدة قطاعات خلال العقد المقبل.



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APPROVAL PAGE

I certify that I have supervised and read this study and that in my opinion, it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Master of Science in Mechanical Engineering.



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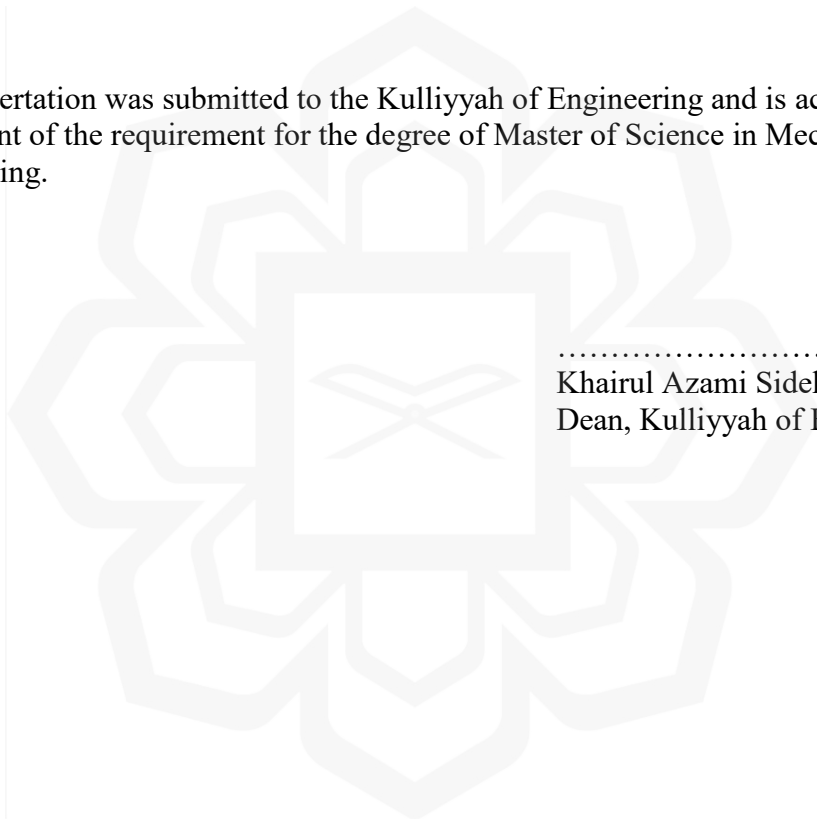
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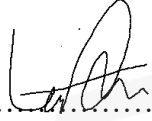
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*This dissertation is dedicated to my late parent for laying the foundation of what I
turned out to be in life.*

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LIST OF SYMBOLS

GWP	Global Warming Potential
HEV	Hybrid Electric Vehicle
PHEV	plug-in hybrid electric vehicles
USGS	United States Geological Survey
LCA	Life Cycle Assessment
SF ₆	Sulfur Hexafluoride
EB	Engine Block
CO _{2e}	CO ₂ -equivalent
GHG	Greenhouse Gas
AHSS	Advanced High-Strength Steels
CFRP	Carbon Fiber-Reinforced Polymers
SO ₂	Sulfur Dioxide
EV	Electric Vehicle
ICE	Internal Combustion Engine
WTW	Well-to-Wheel
WTT	Well-to-Tank
CVT	Continuously Variable Transmission
TTW	Tank-to-Wheel
FRV	Fuel Reduction Value
MFA	Material Flow Analysis
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
CFRP	Carbon Fiber Reinforced Polymer
CGI	Compact Graphite Iron
LPS	Lightweight Structural Materials
Fe	Cast Iron
EPA	U.S. Environmental Protection Agency

PTW Pump-to-Wheel
CED Cumulative Energy Demand
VMT Vehicle Miles Traveled
ADR Assembly, Disposal, and Recycling



CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND OF THE STUDY

Environmental considerations, most notably climate change, have accelerated the emphasis on carbon emissions and resource efficiency in automotive manufacturing. Cars emit greenhouse gas (GHG) emissions directly when burning fossil fuel and indirectly during the materials and energy needed for its production. As Ian Tiseo (2024) mentioned, Global CO₂ emissions are rising year after year (as shown below in Figure 1.1). This graph tracks the steady rise in annual carbon dioxide emissions from around 5 billion metric tons in 1940 to over 35 billion metric tons in recent years. The data is from October 2023, noting that the carbon footprint of industrial processes and energy production activities is growing steadily.

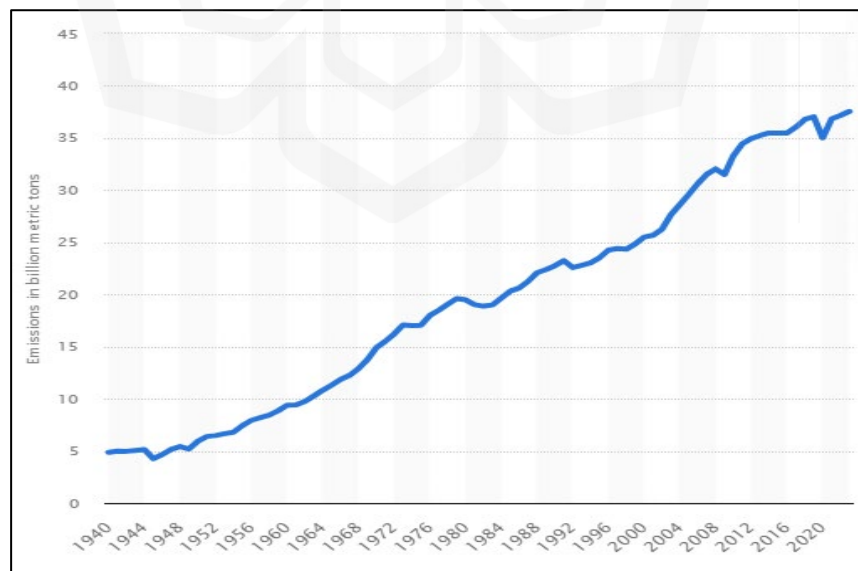


Figure 1.1 Annual Global CO₂ Emissions (1940–2023) (Ian Tiseo, 2024)

The automotive industry, in turn, is using Life Cycle Assessment (LCA) — a tool that quantifies the environmental impact of a product from raw material extraction to end-of-life disposal. LCA enables manufacturers to assess their full life cycle and make educated design decisions that reduce carbon footprint and increase sustainability. Using lightweight materials is one way to reduce automotive emissions. Decreasing the body weight of vehicles can reduce fuel consumption, leading to reduced GHG emissions while increasing fuel efficiency. Magnesium (Mg) and Aluminum (Alu) are lighter metals that have been leading contenders for components such as the transmission systems where strength and weight are very important. Mg is roughly 33% lighter than Alu, which will likely result in fuel economy improvements, but it does also have more energy-intensive production processes, which tend to drive up its overall environmental footprint.

The projected compound growth rate forecast for the global lightweight automotive materials market is shown in Figure 1.2. The market revenue is also estimated to grow from USD 88.31 billion in 2024 to USD 121.80 billion by 2029, growing at a Compound Annual Growth Rate (CAGR) of 6.64%. This increase is attributed to an automotive industry move towards lighter vehicles to reduce the amount of fuel used per mile, and to comply with ever-increasing emissions premises. Design elements in various forms—Alu, Mg and composites among them—have become more prevalent in automotive applications, providing manufacturers with means to perform better and improve the environment. This growth underlines the necessity for the continued innovation and investment in lightweight material technologies to support sustainability objectives (Horizon Markets, 2024).

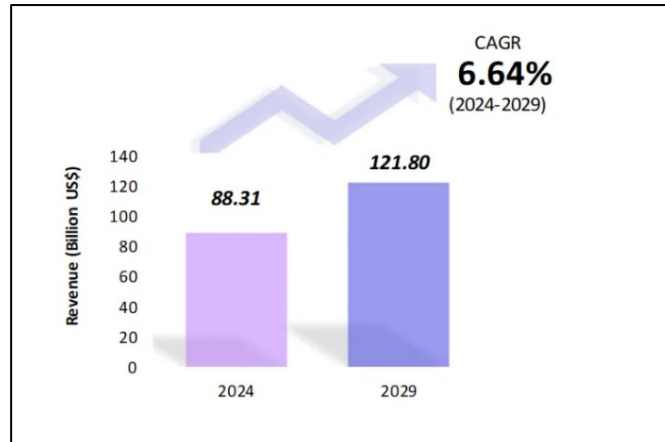


Figure 1.2 Projected growth of the global automotive lightweight materials market (Horizon Markets, 2024)

1.2 STATEMENT OF THE PROBLEM

The transmission system as a part of the powertrain system is one of the heaviest parts of the cars. It is heavy, so getting solutions to reduce the weight of the transmission system matters a lot to reduce the total vehicle weight. A lightweight vehicle consumes less fuel which makes less nitrogen oxide and carbon monoxide emissions. Transmission systems are often made by Alu as it is strong and rust resistant. But as the automotive industry looks to reduce emissions and increase fuel economy, lighter materials such as Mg are being considered. Mg is around a third lighter than Alu, further decreasing the vehicle's weight and emissions while in operation.

However, Mg is challenging to work with. While it could reduce emissions during a vehicle's life cycle, its production process emits more greenhouse gases than Alu, partly due to the use of Sulfur Hexafluoride (SF_6) gas in casting. That leads to an uncertain trade-off between Mg production and the application phase. To know its true impact, we need to assess if the advantages of utilizing a conventional component laced with a lighter material

outweigh its production environmental costs. The trade-off between Mg's stronger emissions in the production stage and its possible emissions-reducing potential during the operational stage of the vehicle must be considered.

1.3 OBJECTIVES OF THE STUDY

The objectives of this study are:

1. To compare the life-cycle environmental impacts of Mg and Alu transmission systems, from material extraction to vehicle disposal.
2. To evaluate the trade-offs between the higher production emissions of Mg transmission systems and its potential to reduce vehicle weight and operational emissions.

1.4 RESEARCH QUESTIONS

The study is conducted based on these research questions:

1. What are the life-cycle environmental impacts of using Mg versus Alu for transmission systems in automotive applications?
2. How do the production-phase emissions of Mg compare to the potential emissions reduction during the operational phase when used in the transmission system?

1.5 SIGNIFICANT OF THE STUDY

This study focuses on two key aspects: environmental sustainability and material selection guidance. By comparing the life cycle impacts of Mg and Alu transmission systems, it offers insights into reducing greenhouse gas emissions and achieving stricter environmental standards. Mg, being lighter than Alu, presents a significant opportunity to lower vehicle weight, improve fuel efficiency, and cut emissions, aligning with global sustainability goals. Additionally, the study provides valuable guidance for engineers or designers by highlighting the environmental trade-offs and benefits of each material, enabling more informed decisions for lighter, eco-friendly vehicle designs.

1.6 SCOPE OF THE STUDY

The aim of this analysis is to evaluate the environmental impacts of using magnesium (Mg) and aluminum (Al) as materials for automotive transmission systems. The scope includes the following key aspects:

1. **Life Cycle Assessment (LCA) Comparison:** Performs a complete LCA on Mg and Alu transmission systems, including all life cycle stages which are production, use, and end-of-life. This evaluation will give a full picture of the environmental impact from each material, including energy used and greenhouse gas emissions.
2. **Key Impact Categories:** The assessment highlights categories with particular importance for the automotive sector, including the carbon footprint, energy consumption, and potential emissions reductions in the vehicle's use phase. Focusing on this supply chain will expose the tradeoff between environmental costs of production and the benefits of reduced vehicle weight.

3. **Materials Evaluation Method:** The study assesses environmental impacts of both materials using Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) model. The output is a well-calibrated analysis of energy and emissions that complies with common LCA standards in industry.
4. **Case Study: Transmission system** in the study we focus on the transmission system as an example component in the power train system. Although other components of the vehicle contribute to weight and emissions, this study focuses on the transmission system having in mind that it is one of the heaviest components of the vehicle, which makes it easy to define the analysis scope.
5. **Material Selection Guidelines:** This will be translated into material selection guidelines based on the above comparative analysis that can be used by the automotive industry for lightweight design. Instead, it provides an analysis of the processes that are available to manufacturers for Mg and Alu and, as such, it does not put forward new manufacturing methodologies but rather provides an overview to allow manufacturers to make decisions based on current best practices.

CHAPTER TWO

LITERATURE REVIEW

2.1 INTRODUCTION

Environmental pressures are greater now than ever, due to rising pollution especially climate change driven by greenhouse gas emissions. Many human activities especially large industrial operations, release a lot of carbon emissions. Over time, this leads to negative effects on both human health and nature. Carbon footprint is the total of greenhouse gases (mainly CO₂) emissions caused directly or indirectly by a person, organization, event or product. It is usually measured in tons of CO₂-equivalent (CO₂e) per year. Activities such as burning fossil fuels to obtain energy, manufacturing, transportation and deforestation contribute to an increased carbon footprint. Reducing carbon footprints emphasizes reducing greenhouse gas emissions by increasing energy efficiency, switching to renewable energy sources and decreasing fossil fuel use.

The increasing carbon footprint over the years is one of the primary reasons for global warming and climate change which creates extreme weather, sea level rise and loss of biodiversity. This degradation affects not only ecosystems but also human health, as air and water pollution are associated with the spread of respiratory and waterborne diseases, especially in urban environments characterized by high population density and pollution concentrations. To mitigate these intense environmental impacts, making this carbon footprint smaller by reducing emissions would be necessary (Tyagi et al., 2014).

Discounting environmental degradation, including the climate change brought on by carbon footprints, everyone should be responsible for this problem. This is particularly

relevant for sectors that engage in significant production, like the automotive sector. To reduce negative environmental impacts and develop sustainable products, business and industry leaders need to weigh critical decisions throughout product development. To ensure the physical wellness of everyone around the globe, LCA can help encourage these important decisions for the sake of our planet's wellbeing.

2.2 LIGHTWEIGHT MATERIALS IN AUTOMOTIVE APPLICATIONS

2.2.1 General Lightweight Materials

Many automotive designs utilize lightweight materials to cut down on vehicle mass. Less weight, better mileage, fewer emissions, and better performance, without losing strength or safety. They are particularly beneficial for applications such as wheels, frames, and transmission parts, where weight savings lead to directly reduced energy consumption. Automakers meet stricter environmental standards while maintaining durability and functionality by utilizing lightweight materials. Table 2.1 shows the various alternative lightweight materials used in automotive design.

Table 2.1 The alternative lightweight materials used in automotive design.

No	Material	Component	Remark	Reference
1	Advanced High-Strength Steels (AHSS)	Body structures, crash zones, reinforcements, roof rails.	Applied high strength for safety and without the need for additional mass.	(Czerwinski, 2021a)
2	Alu Alloys	Engine blocks, body panels, suspension systems, frames, wheels.	Follow the right amount of strength and lightness. Features: Lightweight, High strength, Used for structural & non-structural components.	(Taub & Luo, 2015)
3	Mg Alloys	Steering wheels, seat frames, instrument panel structures, transmission casings.	One of the lightest structural metals, great for weight-critical applications.	(Haber, 2018)
4	Carbon Fiber-Reinforced Polymers (CFRP)	Body panels, roof structures, chassis, aerodynamic parts.	Great strength-to-weight ratio, used in performance-based designs.	(Czerwinski, 2021a)
5	Metal Matrix Composites (MMCs)	Brake discs, pistons, cylinder liners, connecting rods.	Metals combined with ceramic or other reinforcements for greater strength and lower weight.	(Haber, 2018)

6	Polymer Matrix Composites (PMCs)	Interior trims, dashboards, bumpers, non-structural panels.	Include materials such as fiberglass and thermoplastics – used for interior pieces and non-structural components because of their lightweight, moldable nature.	(Haber, 2018)
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In recent years, the emphasis on sustainability has accelerated the use and development of Multi-Material Lightweight Vehicle (MMLV) designs, which combine various materials (Alu with steel, for example) in different proportions to minimize weight while maximizing strength, as exemplified by Porsche's Taycan Electric Vehicle (EV) shown in Figure 2.1. As an example, the MMLV's mass was 23.5% lower compared to traditional vehicles, and die-cast and forged Alu components were employed throughout the Taycan EV to maximize efficiency. This is evidence to the key role of lightweight materials in improving overall automotive performance and achieving environmental objectives (Czerwinski, 2021).

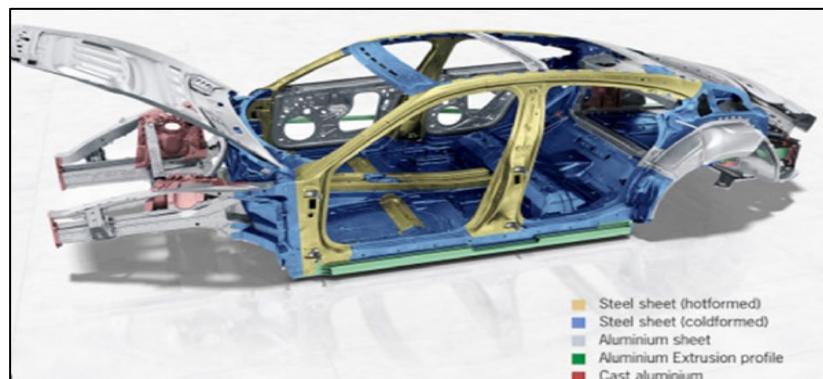


Figure 2.1 Multi-material designs of ICE and EV (body-in-white) (Czerwinski, 2021)

The following is a comparison of mass reduction versus lightweight and traditional material in Figure 2.2. Mg (30–70% weight reduction) and carbon fiber (50–70% weight reduction): These two types of composite materials represent the richest persistence of 1 set of used, having low density and high strength, while gaining the most significant weight reduction. Alu and its alloys deliver 30-60% lighter components and are favored for weight savings that are also cost-effective; titanium reduces weight by 40-55% but is deployed in only niche components given its exceptional strength and corrosion resistance. While Advanced High-Strength Steels (AHSS) is heavier, it can yield 15-25% (reductions) and it is very cost-effective and requires less energy to produce. These developments determine the emphasize on using variety of materials to mitigate mass, performance as well as sustainability (U.S. Department of Energy, 2015).

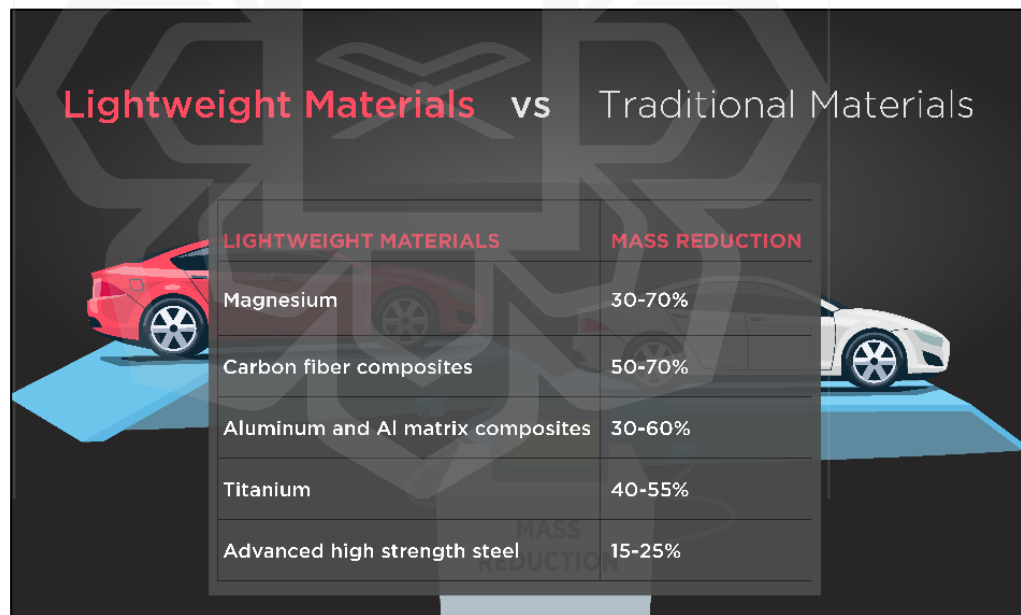


Figure 2.2 Comparison of mass reduction between lightweight and traditional materials (U.S. Department of Energy, 2015)

2.2.2 Mg as Lightweight Material

One of the promising alternative lightweight materials for replacing conventional materials in vehicles is Mg. Mg can be used to decrease the vehicle's weight, which leads to lower fuel consumption while reducing environmental pollution. In the last decade, lightweight materials and lightweight construction became key focal points. According to (Khademian & Peimaei, 2021) so Mg alloys have a considerable lightness comparing with Alu and steel and it can be a great candidate for automotive lightweighting which plays a vital role in the fuel efficiency and emission reduction. Mg is one of the light structural metals, with a specific weight of 1.74 g/cm^3 , which is about 33% lower than Alu and 75% lower than iron. This weight-saving capability makes Mg an excellent material for automakers striving to create vehicles that meet eco-friendly regulations and improve fuel economy.

Mg alloys are commonly used in automotive components as they offer a low density and strength to weight ratios that can be used for weight savings on many components of a vehicle. Figure 2.3 shows the Mg application in automotive. These alloys are used in components including transmission cases, engine cradles, and seat frames. These components help improve fuel efficiency and reduce emissions by reducing the overall weight of the vehicle. The distinctive properties of Mg make it the material of choice for light and high-performance automotive components alike, complementing efforts across the industry to evolve towards more sustainable designs.

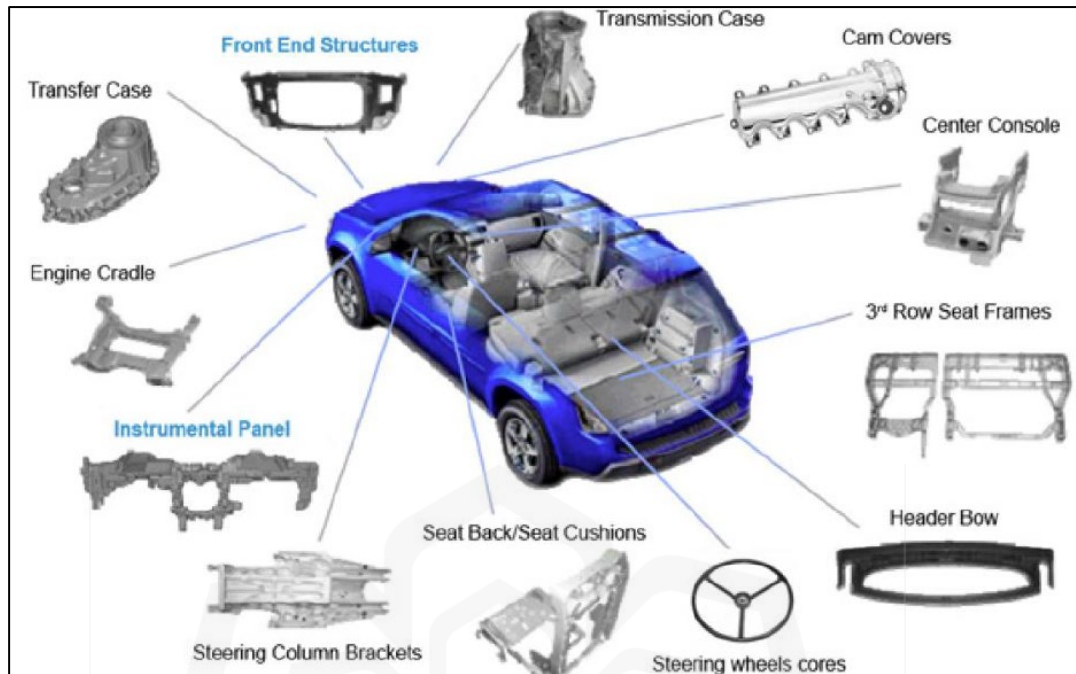


Figure 2.3 Mg application in automotive (Khademian & Peimaei, 2021)

In addition, several characteristics of Mg make it advantageous for automotive lightweighting, including high specific strength, good castability, and excellent damping properties, all of which improve handling and reduced noise and vibration in the vehicle (Dziubinska et al., 2024). Mg is also very recyclable, which can decrease lifecycle emissions. But Mg is not widely used for mass production, mainly due to its high production cost, vulnerability to corrosion, and lower mechanical strength than steel or Alu under higher temperatures. Such constraints often limit Mg usage to non-essential and low-load components (Dziubinska et al., 2024) (Ehrenberger & Friedrich, 2013).

To address these shortcomings, much of the recent work has focused on alloy design and property optimization. For example, there have been some promising efforts to modify the alloys to increase their strength and resistance to corrosion, making Mg more suitable for structural applications in vehicles. Alloying to increase durability, to make Mg alloying

more competitive with other materials like Alu or high-strength steel is also being explored further. Additionally, Mg alloys improve upon Alu as they are more formable (have longer end life) and solidify more quickly (less latent heat) so a greater number of components can be produced per unit time (Just Auto, 2017).

Table 2.2 presents selected review papers addressing Mg development efforts to mitigate its limitations. This table summarizes the progress in Mg alloys as a potentially valuable automotive material, focusing particularly on overcoming limitations such as environmental impact, corrosion-free behavior and durability under high-energy conditions. The study highlights the Mg and silicon alloy, rare earth metals and Alu were used to enhance strength and stability in automotive components prone to wear and tear. Therefore, Mg is one of the most potential lightweight materials to replace the conventional materials in automotive, as it minimizes the environmental impacts.

Table 2.2 Review of Mg Development as Vehicle Component's Material

No	Source	Focus Area	Key Improvements	Application Focus
1	(Kaplan et al., 2000)	Development of Mg alloys with Alu and rare earth metals to improve high-temperature stability and creep resistance, making it more suitable for high-stress components.	Alloying with Alu, rare earth metals, and silicon to boost creep resistance and high-temperature stability.	Transmission cases, powertrain components.
2	(Kulekci, 2008)	Advancements in coating technologies for enhanced corrosion resistance, expanding Mg's applicability in powertrain components subjected to harsh environments.	Use of protective coatings to improve durability and corrosion resistance in transmission cases and powertrain parts.	Powertrain and high-stress automotive parts.
3	(Ehrenberger & Simone, 2020)	Lifecycle assessment of Mg, emphasizing continuous improvements in production processes and alloy composition to strengthen performance in automotive transmission systems.	Sustainable production methods and optimized alloy composition for better environmental impact and enhanced high-temperature durability.	Automotive transmission systems and lightweight structural components.
4	(Kim & Han, 2008)	Development of high-temperature Mg alloys (e.g., AZ91D) to improve strength and durability for components like the transmission case, engine oil pan, and cylinder block in Hyundai and Kia vehicles.	Efforts in improving high-temperature performance of Mg alloys, specifically to enhance its applications in powertrain parts.	Powertrain components, including transmission case, oil pan, cylinder block.
5	(David L., 2017)	Enhanced manufacturability and longevity of Mg alloys, including faster solidification and improved die life, allowing higher component production rates than Alu.	Alloying with elements like arsenic to significantly reduce corrosion rates.	General automotive components production for enhanced fuel economy and performance.

2.3 LIFE CYCLE ASSESSMENT (LCA)

LCA is a scientific method that is used to calculate the impact of a product or service on the environment. Although there are many LCA standards available as a reference, this paper mainly focuses on International standards, namely ISO 14040 and ISO 14044 as a backbone for LCA, which standardised the principles of LCA. ISO 14044 offers comprehensive instructions for carrying out LCA's four phases—Goal and Scope definition, Life Cycle Inventory (LCI), life cycle impact assessment (LCIA), and Interpretation while ISO 14040 lays out the general framework and guiding principles of the process. These guidelines work together to create a systematic method that assesses a product's environmental effects across the course of its lifecycle. The LCA process, as shown in Figure 2.4, consists of four interconnected phases, each providing a structured approach to assessing environmental impacts.

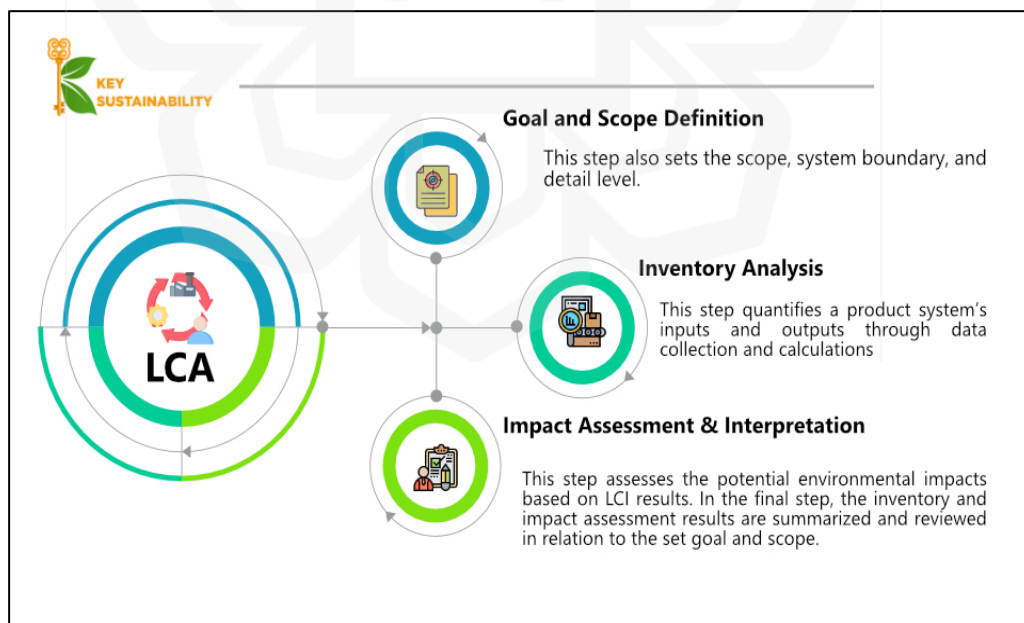


Figure 2.4 The Four Phases of Life Cycle Assessment (LCA) as outlined by ISO 14040 and ISO 14044 (Key Sustainability Solutions Pvt Ltd., 2024)

Based on ISO 14040 and 14044, environmental impact assessment of a product is divided into four stages. Goal and Scope Definition defines the goals and boundaries of the LCA. LCI analyzes energy, materials, and emissions in a lifecycle. LCIA assesses environmental impacts such as climate change, human health, and ecosystems. Finally, Interpretation is focused on reviewing outcomes to verify they meet objectives and that they are guiding sustainable choices. Additionally, it ensures a holistic perspective on a product's environmental footprint, which would enable more informed approach to sustainable practices (Key Sustainability Solutions Pvt Ltd., 2024).

On the first phase of Goal and Scope Definition, the type of life cycle stages of the product needs to be decided. Figure 2.5 illustrates the Product Life Cycle and its connection to LCA and environmental impacts, including the carbon footprint. It shows that each stage of the product life cycle—Raw Material, Processing, Transportation, Retail & Use Phase, and Waste—contributes data on energy use, emissions, waste, and materials. Depending on the scope and available data, certain phases may be included or excluded from analysis. There are three main lifecycle scopes. Firstly, Cradle-to-gate which assesses impacts from raw material extraction to when the product leaves the factory, excluding distribution, use, and disposal. Next is Cradle-to-grave which covers the full lifecycle from raw materials to end-of-life waste treatment and finally Cradle-to-cradle, a circular approach that aims to create regenerative systems, transforming products from traditional linear use to sustainable, closed-loop cycles to minimize environmental impact.

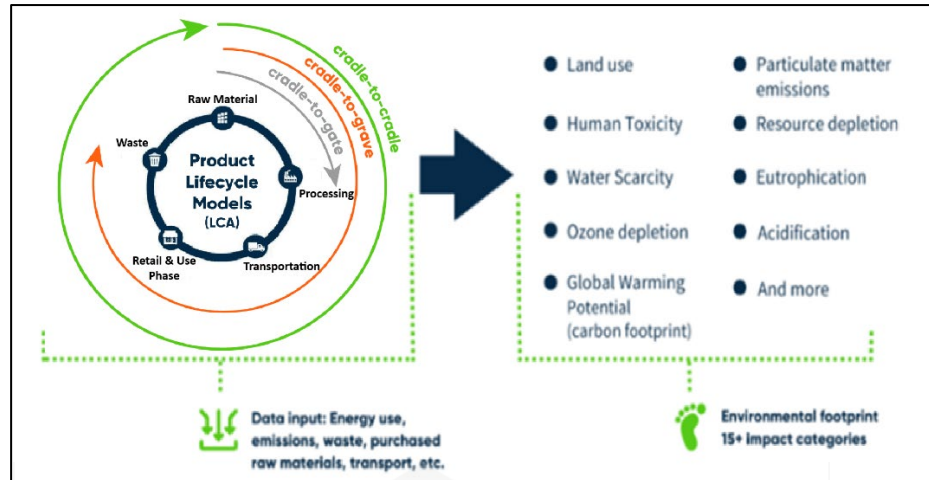


Figure 2.5 The Product Life Cycle and Environmental Footprint Impact Categories
(Ecochain, n.d.)

LCA uses these data to assess multiple environmental impact categories including Global Warming Potential (carbon footprint). While the carbon footprint specifically measures greenhouse gas emissions related to climate change, LCA provides a broader view of the environmental footprint by evaluating additional categories, enabling the industries to make more sustainable decisions across the product's entire life cycle.

The next phase, LCI phase is responsible for the collection of detailed data on all exchanges between the product systems and the environment as well as on the consumption of resources including natural resources, emissions into air, land and water. This phase assesses the environmental engagements of the product lifecycle at all the stages of its lifecycle, from the extraction of raw materials to the disposal of the product at the end of its life. LCI that consists of a lot of hundreds of items is fundamental to identify environmental consequences. As an illustration, the ecoinvent database is one of the most implemented in automotive life cycle assessments, providing information on fine details at the vehicle parts and production process levels. Its adaptable characterization allows linked

analysis of a common operational unit, such as emissions and resource use, across vehicle types, making it a suitable creation for automotive analysis (Del Duce et al., 2016).

The third stage of LCA, LCIA uses specific impact assessment methods to interpret the data from the LCI and measure the environmental harm. With this inventory data, the LCA software will calculate the impacts, sorting them into categories like pollution, resource depletion, and climate change. In this phase, the product's environmental impact is quantified across those impact categories, offering a clearer view of the product's overall environmental effects, as well as allowing comparisons or improvements with regard to its lifecycle sustainability (Ecochain, n.d.).

There are several commonly used formulas in LCA to quantify the environmental impacts. The Life-Cycle GWP formula calculate totals greenhouse gas emissions by adding the contributions from the production, use, and disposal phases. It is expressed as:

$$GWP_{total} = GWP_{production} + GWP_{use\ phase} + GWP_{end-of-life} \quad (1)$$

Operational Emissions Reduction formula calculates the decrease in emissions due to weight savings and better fuel economy over a product's lifecycle. It is expressed as:

$$\Delta E = m \times F \times d \quad (2)$$

Where:

- m : Mass reduction (kg).
- F : Fuel efficiency improvement factor (e.g., liters saved per kg reduction per km).
- d : Distance traveled over the vehicle lifetime (km).

The Life-Cycle Energy Consumption can be calculated by considering the energy used throughout all stages of a product's life cycle, including production, operation, and recycling. It is expressed as:

$$E_{total} = E_{production} + E_{use\ phase} + E_{recycling} \quad (3)$$

Lastly is the Weight Reduction to Fuel Savings formula, which measures the correlation of reduced weight to fuel savings- a key measurement when lightweight materials are applied: -

$$\Delta F = \Delta m \times f \quad (4)$$

Where:

- ΔF : Fuel saved (liters).
- Δm : Mass reduction (kg).
- f : Fuel efficiency improvement factor (e.g., liters saved per kg).

LCA is referenced through these formulas in order to make sure its widespread standards, and each process would have the same consistency while getting the results.

In order to ease the process for the LCA, particularly for the LCIA phase, various software tools and simulation platforms are widely utilized. SimaPro, GaBi, OpenLCA, GREET and Umberto are well known LCA software. Also, these tools enable us to manage and analysis the complex datasets on which LCA studies are based, with the aim of gathering accurate impact assessments and improving decision processes. For example, databases such as GaBi and ecoinvent are often used by information technology in the automotive field to assess life cycle environmental impacts and potential for environmental improvement. (Sustainable Business & Technology Institute, 2024).

GREET model, developed by Argonne National Laboratory, is a comprehensive tool widely used in transportation studies to evaluate greenhouse gas emissions, energy use, and other environmental impacts across the entire lifecycle of fuels and vehicles. GREET enables detailed well-to-wheel (WTW) assessments, including both well-to-tank (WTT) and tank-to-wheel (TTW) stages, making it an effective model for calculating global warming potential (GWP) and other midpoint environmental impacts (Argonne National Laboratory, n.d.).

Finally, the Interpretation phase in LCA focuses on answering key questions set in the Goal and Scope phase by analyzing which aspects of the product system drive the most significant environmental impacts, such as specific materials or processes. This phase also involves identifying potential trade-offs, where improvements in one impact category (e.g., reducing climate impact by using solar energy) may lead to drawbacks in another (e.g., increased resource depletion due to rare metals in solar panels). Contribution analysis helps pinpoint impact hotspots, or elements with the highest environmental impacts, guiding targeted improvements. The iterative nature of this phase means insights here may prompt adjustments to earlier phases, refining the model for more accurate and meaningful results (Ecochain, n.d.).

For example, in their research on recycling options for automotive Li-ion battery packs, Kallitsis et al. (2022) applied the four-phase LCA process outlined in ISO 14040 and ISO 14044 standards to ensure a comprehensive and transparent environmental impact analysis. They began with the Goal and Scope Definition phase, setting clear objectives to assess the environmental impacts of different recycling methods (hydrometallurgical and pyrometallurgical processes) for battery components. In the Inventory Analysis phase, they collected detailed data on materials and energy use across the recycling process, including collection, disassembly, and materials recovery. For the Impact Assessment, they evaluated the environmental impacts across 13 impact categories including GWP using the ReCiPe 2016 Midpoint characterization method. Finally, in the Interpretation phase, they analyzed the results, identifying hotspots within the recycling process, such as high energy use in pyrometallurgical processing, and recommending improvements. This structured approach demonstrated that hydrometallurgical recycling offered more environmental benefits, notably in reducing GWP, due to higher material recovery rates.

2.4 LIFE CYCLE ASSESSMENT (LCA) IN LIGHTWEIGHT VEHICLE

In the automotive industry, lightweighting is a significant focus in LCA studies for vehicles, as reducing vehicle weight can directly decrease fuel consumption and emissions over a vehicle's lifetime. Lighter vehicles require less energy to operate, which lowers greenhouse gas emissions, especially in internal combustion engine vehicles (ICEVs). In electric vehicles (EVs), lightweighting can extend battery range, thus improving efficiency. However, lightweight materials, like Alu, Mg alloys, and carbon fiber, often require more energy to produce, which can increase the environmental impact during the manufacturing phase. Table 2.3 summarizes the literature review from other papers about the LCA in automotive application focused on lightweighting vehicles.

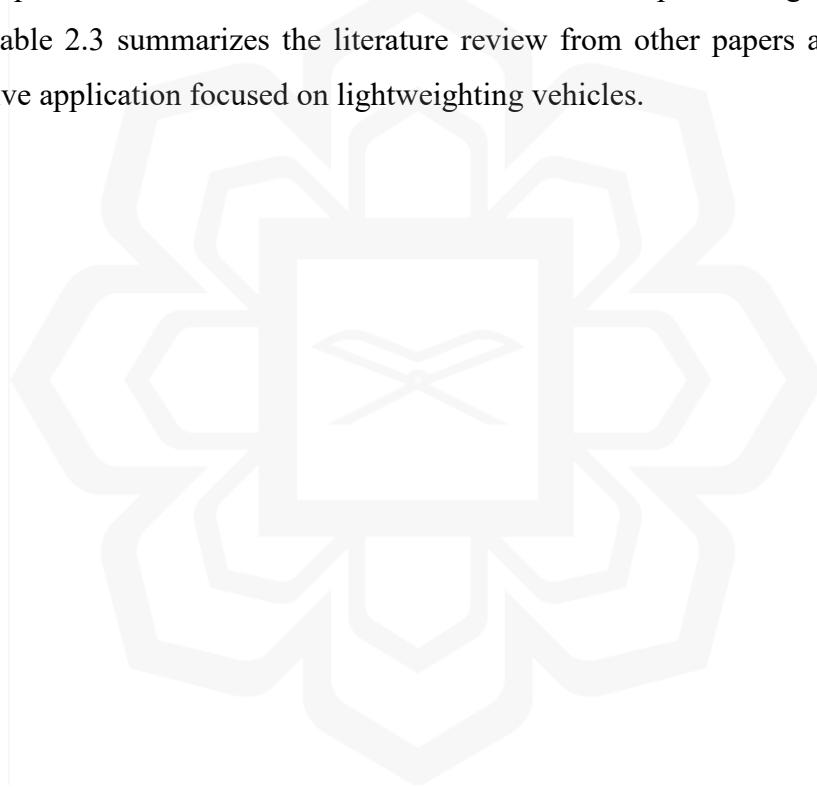


Table 2.3 LCA on Lightweight Vehicles

No.	Reference	Goal and Scope	Functional Unit (FU)	Life Cycle Inventory (LCI)	Life Cycle Impact Assessment (LCIA)	Interpretation / Results
1	(Kelly et al., 2015)	Assess the impact of replacing standard materials with lightweight ones on vehicle GHG emissions, focusing on parts like the engine block and door frame.	Vehicle lifetime (260,000 km), part-level (kg CO ₂ e/ part).	GREET model, literature on lightweight materials, and substitution ratios from reports and industry data.	GREET model, life-cycle assessment, fuel reduction value (FRV) method.	Reduces fuel-cycle GHGs, but emissions from Al and Mg production affect net benefits, depending on driving distance and substitution ratio.
2	(Lewis et al., 2014)	Assess energy use and GHG emissions of lightweight materials (Alu and A/HSS) and different powertrains. (ICV, HEV, PHEV).	Lifetime VMT (160,000 miles) per vehicle.	Electricity and fuel data specific to U.S. integrated with vehicle mass models data from GREET, eGrid, and industry sources.	GREET, eGrid, Autonomie simulation software.	Alu reduces weight more (35%) but has higher emissions. A/HSS gives similar benefits with less impact. ICVs cut GHGs most, while PHEVs benefit from regenerative braking.
3	(Golroudbary et al., 2022)	Goal: Assess Mg as a sustainable lightweight material for cars. Scope: Cradle-to-grave study covering production, use, recycling, and its role in a circular economy.	1 kg of Mg in car parts (e.g., gearbox, steering) used for lifecycle comparison.	Data Collection: USGS, European Commission Reports, Statista Database.	Software: GREET Method: Evaluates energy use, water use, and GHG emissions in production and recycling.	Mg reduces emissions and saves fuel. Recycling offsets its high production emissions, enabling sustainable automotive use.
4	(Salonitis et al., 2019)	Goal: Compare the energy and environmental impact of aluminum vs. cast iron engine blocks, focusing on fuel savings. Scope: Full LCA of engine blocks.	1 engine block molded from cast Alu or iron.	Data Collection: Egrid, Industry reports and surveys.	Software Used: None stated; calculation based on collected data and literature.	Aluminum reduces fuel consumption due to lower weight, with benefits noticeable only after significant mileage. It is more sustainable through recycling.

5	(Kiefer et al., 1998)	Goal: Perform an LCA of steel and magnesium cross car beams, comparing environmental impacts across production, use, and end-of-life phases.	1 cross car beam over lifetime mileage (150,000 km).	Software Used: GaBi 2.0, with data from industrial sources, country-specific energy mixes, and recycling processes.	GaBi 2.0; Life cycle Engineering framework with FRV included.	Magnesium reduces use-phase energy but has a high GWP due to production energy and SF ₆ emissions. Its sustainability improves with recycling and SF ₆ alternatives.
6	(Tharu marajah & Koltun, 2007)	Assess the environmental benefit of Mg compared to Alu in automotive programs looking at emissions in the production and use stages.	1 unit of engine block (EB).	Published sources, industry communication, SimaPro database and previous studies.	SimaPro software	Magnesium reduces use-phase emissions but has higher production emissions than aluminum. Using HFC-134 or SO ₂ instead of SF ₆ improves sustainability.
7	(Liu et al., 2022)	Goal: Analyze recycling impacts using different allocation methods (e.g., cut-off, avoided burden) for Mg, aluminum, and AHSS in lightweight vehicles, focusing on GHG emissions.	1 compact vehicle with a lifetime of 200,000 km.	Ecoinvent v3.4, material flow analysis (MFA) for yield rates and recycled content, and industry data sources.	Attributional and consequential LCA (cut-off and avoided burden approaches).	Recycling affects material choice. Aluminum has lower GHG emissions than magnesium due to its production. Recycling benefits are higher for BEVs than ICEVs.
8	(Shen et al., 1999)	Life Cycle Comparison of a Powertrain Structural Component made Tolainuerve® Mg vs. Diecast Alu. LCA with a cradle-to-grave approach.	1 powertrain (200,000 km vehicle life).	Thixotech Inc. together with Ford industry reports and Ecobalance (DEAM™ database).	LCAdvantage™ software	Magnesium reduces use-phase emissions but has high raw material burdens, including SF ₆ . Recycling aluminum is beneficial due to energy, water, and land use reductions.
9	(Dubreuil et al., 2010)	Compare energy and environmental impact for Mg, Alu and steel front-end automotive parts for a GM Cadillac CTS over 200,000 km vehicle lifetime. Cradle-to-grave LCA.	1 unit of front-end assembly (GM Cadillac CTS).	Ecoinvent database, industry sources, and GREET; uses world averages for material production with North American context.	SimaPro Software.	Magnesium reduces weight and fuel use but has higher production energy. Aluminum reaches GHG breakeven sooner. Improved production and recycling can lower magnesium's footprint.
10	(Du et al., 2010)	Life cycle GHG emissions and energy usage assessment for automotive Mg hafnium applications: production to end-of-life stages. Cradle-to-grave LCA.	1 base automobile (200,000 km lifetime).	Primary data from Chinese factories (Pidgeon process), GREET model, and secondary data (ecoinvent, literature).	GREET model.	Lifecycle GHG emissions reduction potential from substituting Mg; however, high energy requirements of Pidgeon method dampen total benefits.

For example, in LCA considerations of lightweight vehicles, the trade-off between production impacts and utility in the operation phase is generally compared (Kelly et al., 2015) (Tharumarajah & Koltun, 2007) (Salonitis et al., 2019) (Dubreuil et al., 2010). For instance, breakeven driving distances for the GHG emissions on substitution of conventional materials by lightweight alternatives (Al, Mg, and CFRP) are illustrated in Fig. 2.6. It reveals the trade-off with higher production-phase emissions and use-phase fuel savings. Replacement combinations such as steel-to-Alu yield closer breakeven distances owing to the smaller production impacts of Alu in comparison to steel-to-Mg or steel-to-CFRP, which demand longer vehicle lifetimes to nullify their greater upfront emissions. Moreover, increases in FRV lead to a marked reduction in breakeven distances, pointing toward the significance of fuel efficiency benefits in rendering lightweight materials environmentally viable over the life of an automobile (Kelly et al., 2015).

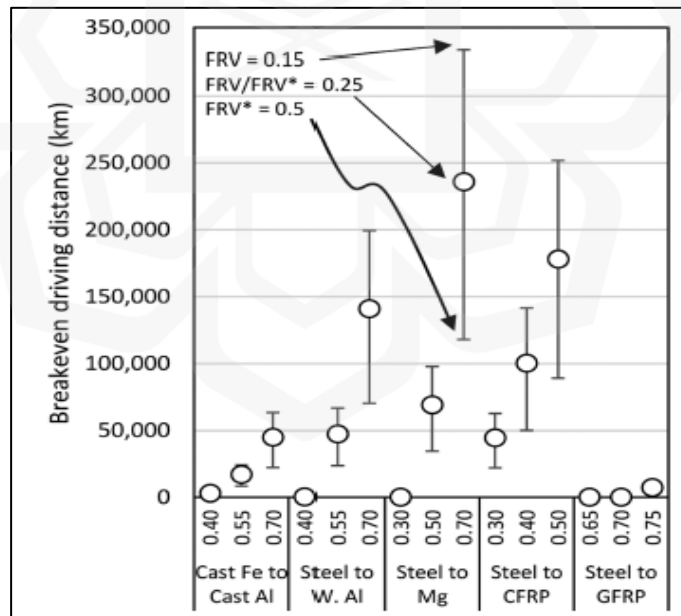


Figure 2.6 Breakeven driving distance for different material substitution pairs and substitution ratios, assuming different FRV/FRV* values (Kelly et al., 2015).

In addition, Figure 2.7 shows the GHG emissions for various engine block systems, separating production and use calculations. Mg and Alu, which are similar in strength-weight properties, show differences in emission profiles. From the results on the use phase emissions, it is also visible that even though Mg provides a high production emission, the total emissions are much lower because the gain in weight reduction has a positive impact in the use phase (i.e. every kg less in the vehicle would mean that 4.3 kg less CO₂ would be emitted during driving, considering an average car travelling 15,000 km per year). This is also reflected by the reactions of the HM-nom and HM-i Mg-based systems where both of the systems show large UEV savings in the use phase, which would compensate the slight increase in the production phase emissions. Their production emissions for the Mg-based systems have a relatively larger CO₂ contribution compared to conventional materials. Alu systems (i.e. Al AU and Al US) similarly have significant use-phase advantages, but the high-energy primary production step plays a large role in their life-cycle emissions. By comparison, many conventional materials such as cast iron (Fe WO) and compact graphite iron (CGI WO) generate higher total emissions, with an emission intensity primarily caused by their higher weight during the use phase (Tharumarajah & Koltun, 2007).

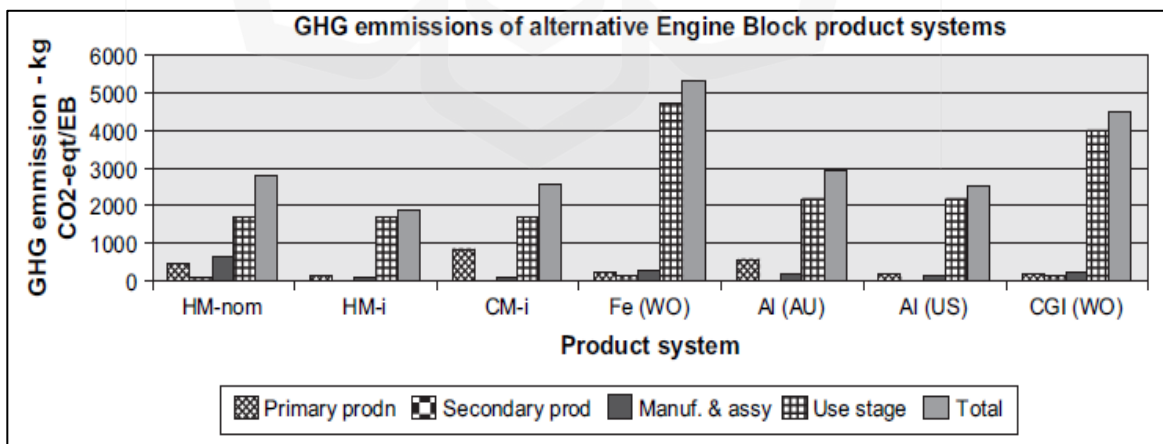


Figure 2.7 Comparison of life cycle GHG impacts for different engine blocks (Tharumarajah & Koltun, 2007).

Next, Figure 2.8 shows the break-even distance for recovering the energy investment of lightweight materials used in automotive manufacturing by comparing manufacturing and use-phase emissions. Lightweight materials such as LPDC (low-pressure die casting), LPS (lightweight structural materials), and HPDC (high-pressure die casting) require a certain driving distance to compensate for the higher energy consumption during their production compared to conventional materials like CISC (cast iron structural components). The analysis highlights the trade-off between the energy-intensive production phase of lightweight materials and the fuel savings achieved during the use phase due to reduced vehicle weight (Salonitis et al., 2019).

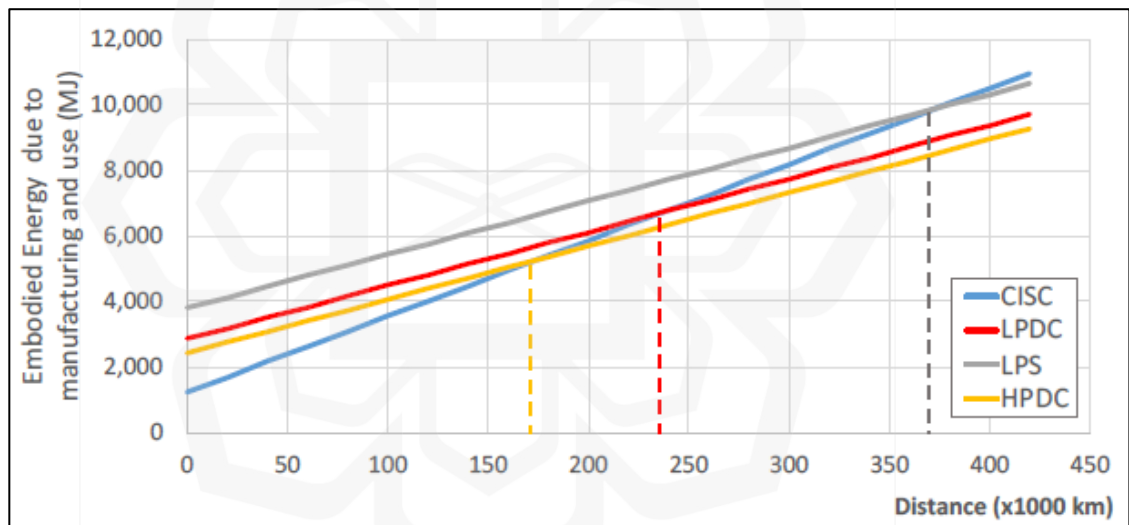


Figure 2.8 Break-even distance for paying back the lightweight material (Salonitis et al., 2019).

Approximately similar GHG emissions across driving distances for automotive steel, Mg, and Alu in components (Figure 2.9). When compared to Alu and steel, Mg has a highlight of emissions during the production phase due to its lower weight and use-phase emissions. Alu has a better breakeven, achieving net GHG reductions and shorter distances

than Mg but Mg needs a much longer distance (Alu: 34,861 km; Mg: 144,461 km) to offset its high production emissions (Dubreuil et al., 2010) (Dubreuil et al., 2010). This underlines the need for trade-off between production and use-phase emissions in the evaluation of lightweight materials for lifetime environmental benefits.

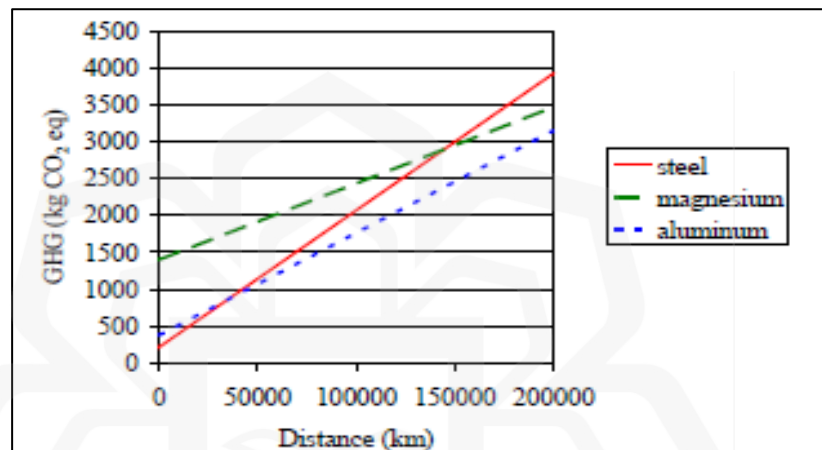


Figure 2.9 Relation Between the GHG and the Driving Distance for Various Front End (Dubreuil et al., 2010)

LCA tools such as GREET, GaBi, and SimaPro have been used by researchers to quantify these trade-offs and allow automakers to make informed decisions about materials that will provide a compromise between environmental impact and performance. LCA research helps promote sustainable vehicle designs based on lightweight materials in the automotive sector that are developed in adhering with regulatory objectives for lowering the total emissions and energy consumption. Automotive LCA topics are dominated by lightweight vehicles with low environmental impact in literature.

Transmission is one of the heaviest parts of the vehicle and using Mg as the dominant material can replace traditional materials such as Alu alloys and steel to achieve significant weight reduction. Although majority of the cars use Alu and steel because the usage of Mg is limited, certain models of car such as A4, A5 and A6 series of Audi brand used it along with a few from Volkswagen and Ford which have used Mg in their transmission systems. Due to its lightweight properties and recent advancements focused on addressing Mg's limitations, Mg has great potential for use in transmission systems. It could be the first or even the best alternative to traditional heavy materials.

However, in most LCA studies related to Mg, especially in the automotive industry, results show that Mg production requires intensive energy and generates higher GWP emissions (Reppe et al., 1998) (Du et al., 2010) (Shen et al., 1999) (Tharumarajah & Koltun, 2007). The GWP of a Mg transmission case is approximately twice that of an Alu case, mainly due to SF₆ emissions from the Mg casting process, which have a significantly higher GWP than CO₂ (Reppe et al., 1998). Figure 2.10 shows the GWP comparison between Mg and Alu transmission cases over the life cycle.

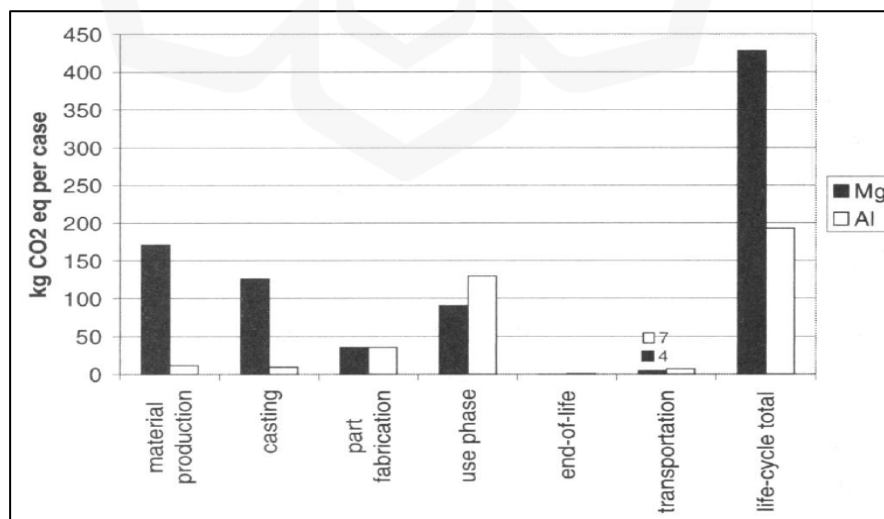
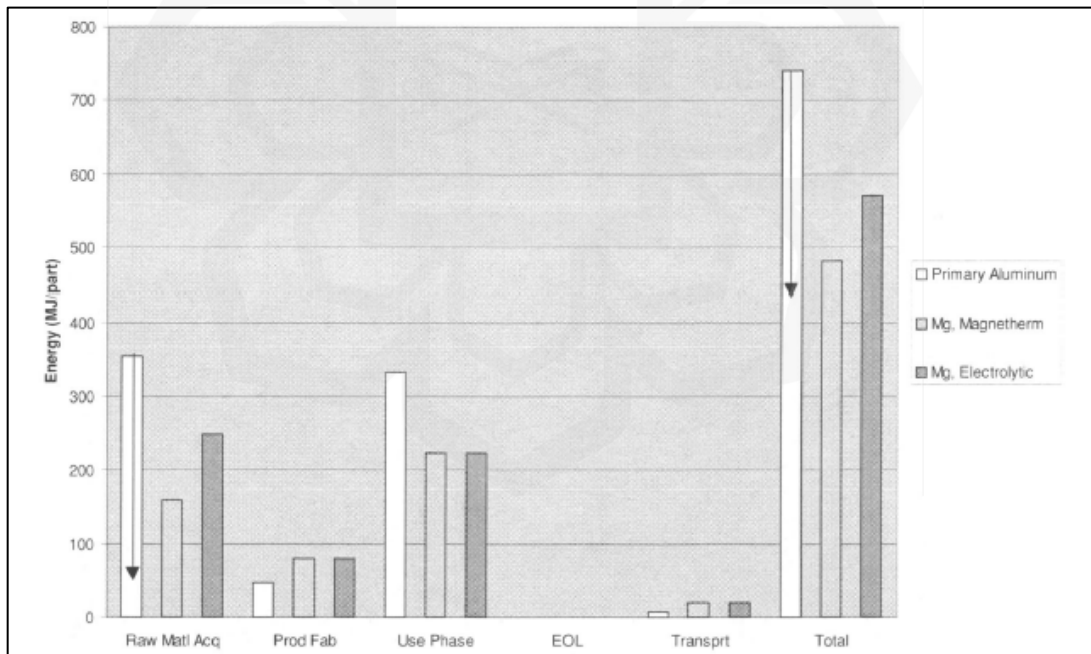
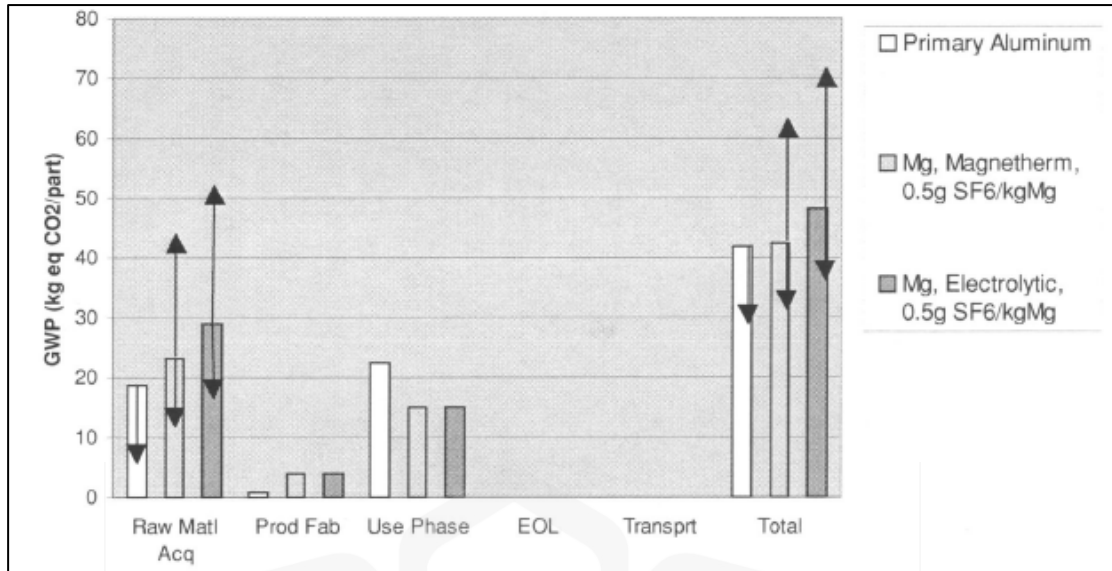


Figure 2.10 GWP Comparison Between Mg and Alu Transmission Cases Over The Life Cycle (Reppe et al., 1998)

Next, Figure 2.11 presents the energy consumption and GWP of production and use of Mg and Alu, and it demonstrates the very high demand on the environment of Mg production. Moreover, SF₆ is used as a cover gas when producing Mg, which has an extremely high GWP and leads to the emission of massive amounts of greenhouse gases. However, the production of Mg is a very climate-damaging industry as it requires fossil fuels and therefore emits a large amount of greenhouse gases. Electrical energy savings associated with substituting secondary for primary Alu are shown as arrows in Figure 2.11a. The single arrow depicted in Figure 2.11b indicates the anticipated reduction in greenhouse gas emissions due to the replacement of secondary Alu with primary Alu. The double arrows are the range of values associated with SF₆ emissions from Mg production (Shen et al., 1999).



a) Energy consumption of Mg and Alu production and use



b) GWP of Mg and Alu production and use

Figure 2.11 a) Energy consumption and b) GWP of Mg and Alu production and use (Shen et al., 1999).

Figure 2.12 discusses GHG emissions and energy consumption of Mg (produced with through Pidgeon and electrolytic processes), Alu, and steel. Pidgeon-produced Mg has much higher GHG emissions (27 kg CO₂eq/kg) and energy consumption (280 MJ/kg), mainly from the use of coal and electricity in production. That is five times greater than steel and about twice that of Alu. The electrolytic production of Mg, which generates slightly lower emissions and energy consumption compared to the pyrometallurgical process, is still greater than for Alu and steel (Du et al., 2010). These results highlight the environmental cost of Mg production, especially compared to lighter alternatives, such as Alu, and underscore the importance of considering environmental impacts during the manufacturing phase when selecting materials for lightweight automotive applications.

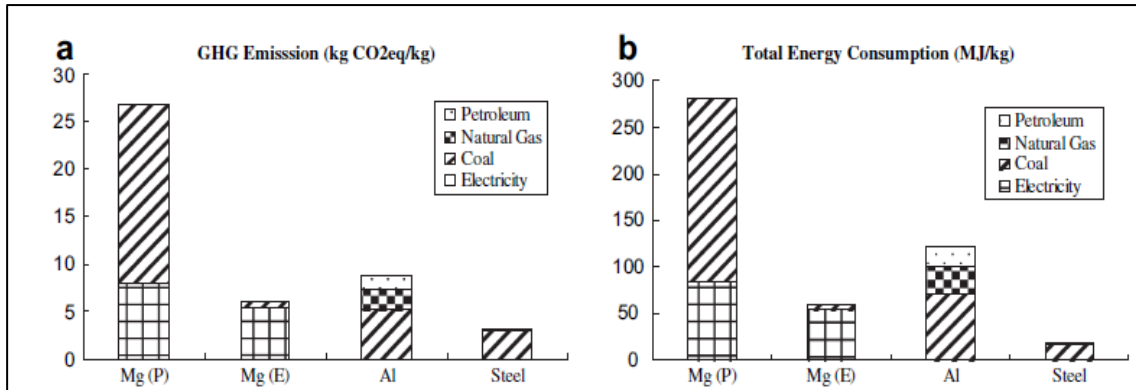


Figure 2.12 a and b Comparisons of GHG emissions and total energy usage between Mg (Chinese Pidgeon), Mg (electrolytic), Al and steel (Du et al., 2010).

For Mg production, SF₆ is applied as a cover gas to avoid oxidation of molten Mg. But its severe environmental impact has spurred efforts to decrease or eliminate its use. The U.S. Environmental Protection Agency (EPA) partnered with Mg industry stakeholders to explore opportunities to cost-effectively limit SF₆ emissions, for example through alternative cover gases (e.g., AM-cover, Novec 612 Mg Protection Fluid, Dilute SO₂, process optimizations) (EPA, n.d.). Novec™ 612 is a sustainable cover gas for Mg casting operations developed by 3M. It is an effective oxidant prevention method while being environmentally friendly compared to SF₆ (3M, 2010).

Continuing to develop Mg extraction and production processes to minimize environmental impact and maximize availability will contribute to its status as one of the most beneficial lightweight elements for use in the auto-industry. Mg is not only suitable for lightweight components, but it also shows potential as a traditional materials replacement for more critical or heavier vehicle parts. It combines a high strength-to-weight ratio with a significant boost in fuel economy, putting it in competition for everything from structural components to powertrain parts such as the transmission system. As an example, the AZ31B Mg alloy reaches tensile strength at 260 MPa and

density of 1.77 g/cm^3 , which results in an approximate correlation of specific strength of $147 \text{ kN}\cdot\text{m/kg}$, and this is undeniable in taking both service performance and ecological benefits into opportunity (AZoM, 2012).

The extensive use of Alu in an automotive transmission system is attributed to its excellent properties, including strength, excellent corrosion resistance, and manufacturability. These properties have made it a popular choice of substance for parts like transmission cases and housing. However, Mg alloys have gained attention as an alternative material because they offer even lower density and a higher strength-to-weight ratio compared to aluminum, making them suitable for further vehicle weight reduction. Despite these advantages, Mg alloys have limitations including poorer corrosion resistance and higher cost than aluminum. The favorability and drawbacks with Alu as well as Mg alloys in automotive are summarized as given in Table 2.4 and 2.5 respectively.

Table 2.4 Comparison of Alu and Mg Alloys properties in Automotive Applications
(Material Properties n.d.).

No.	Property/ Characteristic	Alu Alloys	Mg Alloys
1	Density	~2.7 g/cm ³	~1.74 g/cm ³
2	Tensile Strength	70–700 MPa	138–280 MPa
3	Yield Strength	20–480 MPa	100–160 MPa
4	Young's Modulus	69 GPa	45 GPa
5	Melting Point	~660°C	~650°C
6	Corrosion Resistance	Excellent (oxidation protection)	Requires coatings or anodizing
7	Thermal Conductivity	205 W/m·K	156 W/m·K
8	Specific Strength	Lower than Mg	Higher than Alu
9	Recyclability	Highly recyclable	Recyclable, but less common
10	Cost	Moderate	Higher
11	Ease of Manufacturing	Excellent (widely used in casting, extrusion, etc.)	Good (castable but limited forging or extrusion)
12	Applications	Engine blocks, transmission housings, body panels	Steering wheels, seat frames, lightweight structures
13	Thermal Expansion Coefficient	24 μm/m°C	26 μm/m°C

Table 2.5 Advantages and Disadvantages of Alu and Mg Alloys in Automotive Applications (Material Properties n.d.)

Category	Alu Alloys	Mg Alloys
Advantages	High strength, excellent corrosion resistance, lightweight, highly machinable, cost-effective.	Lowest density among structural metals, high specific strength, weight reduction leads to fuel savings.
	Excellent recyclability, widely available.	Superior vibration damping properties.
Disadvantages	Heavier than Mg, higher melting point increases energy use during production.	Susceptible to corrosion without proper treatment, brittle in thin sections.
	May require higher initial investment for tooling and processing.	Higher production costs, limited availability of high-quality alloys.

In a LCA comparing these two materials, Mg generally performs better in the use phase by lowering vehicles's GHG due to their reduced weight. The primary trade-off between these materials occurs in the production stage, and, while Mg emits more GHG than Alu emissions during the production process (Dubreuil et al., 2010) (Shen et al., 1999) (Tharumarajah & Koltun, 2007).

However, advancements in Mg alloying, corrosion resistance, production and recycling processes as referenced in Table 2 previously shown earlier have indicated some potential from these efforts to address Mg shortcomings, and if production impacts can be minimized Mg can be considered a more sustainable alternative to Alu. Finally, this review

emphasizes the role of life cycle assessment in automotive material selection, achieving a more holistic perspective on environmental costs and benefits within and beyond the vehicle life cycle, and showcasing some governance implications for automotive industry transition towards lightweight and sustainable design.



CHAPTER THREE

METHODOLOGY

Using ISO 14040 and 14044 standards, this study employs a LCA approach to quantify and compare the environmental impact of Mg and Alu in vehicle transmission systems. The analysis is performed through data simulation for which the GREET model was used, developed by Argonne National Laboratory, and for the visualization of the results and evaluation of the sensitivity analysis Microsoft Excel was employed. This methodology includes several crucial steps according to LCA requirements to systematically evaluate environmental performance. The project flow chart is shown in Figure 3.1.



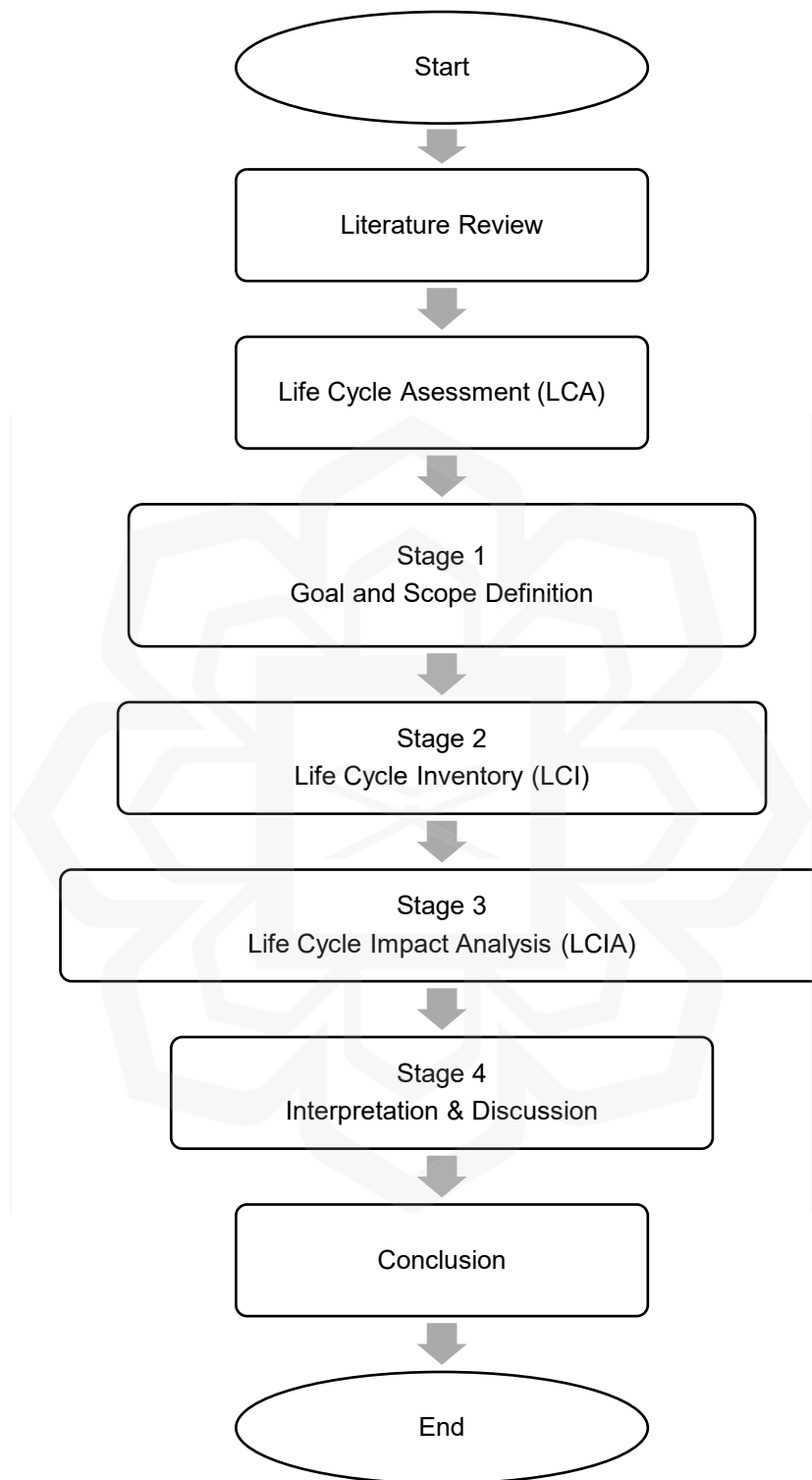


Figure 3.1 Project Flowchart

3.1 GOAL AND SCOPE DEFINITION

The goals and scope of the study is defined to identify the purpose of the analysis, the functional unit for comparison, and the system boundaries. The functional unit ensures consistent comparison between alternatives, while the system boundaries define which processes are included, such as material extraction, production, and use phases to clarify what the study aims to achieve and establish the framework for conducting the LCA. The details are as follows:

3.1.1 Goal

- To evaluate the life-cycle environmental impacts of Mg and Alu in transmission systems.
- To assess the trade-offs between the higher production emissions of Mg and its potential for reduced operational emissions due to weight savings.

3.1.2 Scope

Functional unit for this study is one unit of transmission system weighing 54 kg. This system is a Punch Powertrain VT3 Continuously Variable Transmission (CVT) as shown in Figure 3.2, specifically designed to handle the torque and efficiency requirements of Proton's 1.6L CamPro CFE turbocharged engine as used in Proton Preve (Punch Powertrain, n.d.). The selection of the Proton Prevé's VT3 CVT transmission system ensures a realistic and application-specific evaluation aligned with current automotive practices.

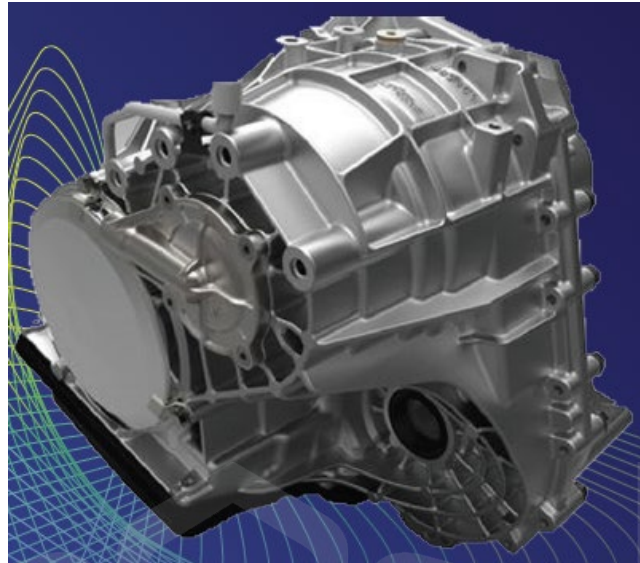


Figure 3.2 VT3 Continuous Variable Transmission (CVT) (Punch Powertrain, n.d.).

This study adopts a Cradle-to-Grave approach for system boundaries which cover product cycle of transmission system until vehicle disposal (Figure 3.3). The assessment includes:

1. Product Cycle:

- Includes raw material extraction, production of the transmission system, vehicle assembly, and vehicle disposal. The assembly stage, which includes machining and finishing operations, was grouped with the end-of-life and recycling processes. This combined stage is referred to as the ADR stage (Assembly, Disposal, and Recycling), based on data from the GREET model. The analysis for Mg production focused on two processes: the Pidgeon process and the Electrolytic process. Both processes were assessed to account for variations in energy consumption and GHG emissions due to differences in raw material sources and production methods. For Alu, data on primary production only were included.

2. Fuel Cycle (PTW):

- Pump-to-Wheel (PTW) covers the fuel combustion during the use phase, Vehicle Miles Traveled (VMT) of vehicles equipped with different weights and types of transmission systems. Since the choice of transmission system does not affect the Well-to-Pump (WTP) phase, the emissions and energy use are measured only during the PTW phase.

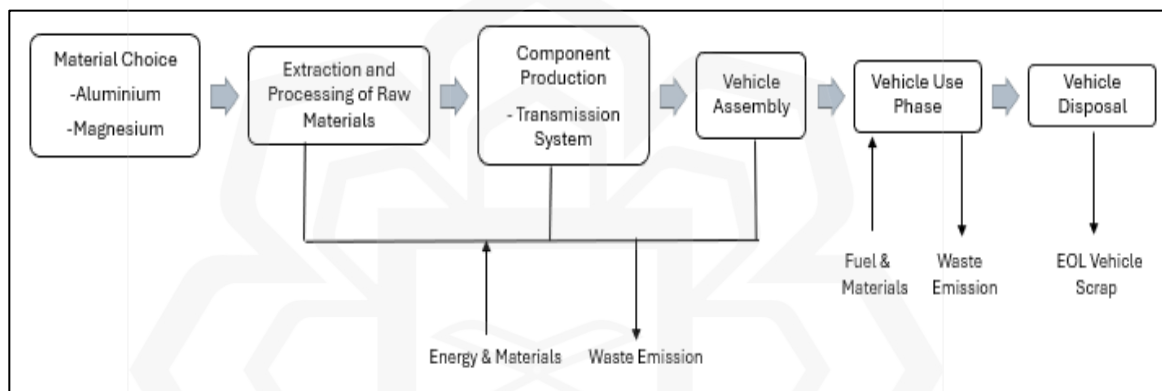


Figure 3.3 Cradle-to-Grave approach

3.1.3 Assumptions

The Proton Preve 1.6 Turbo CVT a passenger car model in Malaysia has a curb weight of 1,340 kg, is equipped with the Punch VT3 CVT transmission system, the reference vehicle for this work is depicted in Figure 3.4 (Car.info. n.d.). VMT per Life Time is 360,000 km, equivalent to average kilometer a car travel for one year per car in Malaysia which was found to be 24,129 kilometers (Shabadin et al., 2014). Some people may also use cars that are more than 10 years old in Malaysia. More than five million vehicles on the road are estimated to be 10 to 15 years old. This indicates that cars in Malaysia have a long usage period, particularly because there is currently no End of Life (EoL) vehicle regulation in

Malaysia (Kassim et al., 2020). Therefore, within 15 years, for this study, average kilometer car travelled per year of 24,000 km assumption is used for calculating VMT. The vehicle that has been measured in this study is shown in Table 3.1.



Figure 3.4 Proton Prevé 1.6 Turbo CVT

The choice of the Proton Prevé model for this project is only consider the vehicle's overall weight, transmission weight, and transmission type that give impact to the use phase results for GHG emissions and energy consumption. But for analyzing total emissions for assembly, disposal, recycling (ADR), material extraction, production phases, and maintenance, the default data is used from the GREET.

Table 3.1 Vehicle Specifications

Specifications	Vehicle Brand & Model	Transmission Types	VMT	Curb Weight	Transmission System Weight	Fuel Consumption
Mg Based Transmission System	Proton Preve 1.6 Turbo	Punch VT3 CVT	360 000 km	1327 kg	41 kg	5.67 L/100km (41.4841 mpg)
Alu Based Transmission System				1340 kg	54 kg	5.7 L/100km (41.2657 mpg) (WapCar. N.d.),

3.2 LIFE CYCLE INVENTORY (LCI)

To conduct the analysis, this study utilized data generated by the GREET 2023 model to calculate energy use and GHG emissions at all stages of a product’s life cycle. For both Mg and Alu, the GREET model supplied all input data needed, including material production, manufacturing, vehicle use, and recycling at end of life. This study extracted data directly from GREET 2023 for this analysis for systems on lightweight passenger vehicle transmissions. The model calculated the energy consumption and GHG emissions for both Mg and Al, respectively. These numbers allowed for calculating the life cycle impacts of each material without the need to make new assumptions or gather additional data.

3.2.1 Primary Aluminum Production

There are several main stages in primary Alu production. Bauxite mining is the first step in Alu production, where bauxite, the ore, is the raw material for the production of Alu. Bauxite is refined into alumina (Alu oxide) via the Bayer process. The alumina is then further processed in the Hall-Héroult process, where it is electrolytically reduced to make Alu metal. Finally, the Alu is poured into molds and cast to ingots or other shapes, ready for use in manufacturing components. This leads to high energy input in every stage of the beverage production process, which makes assessing its environmental impact from life cycle assessment studies needed (Figure 3.5).

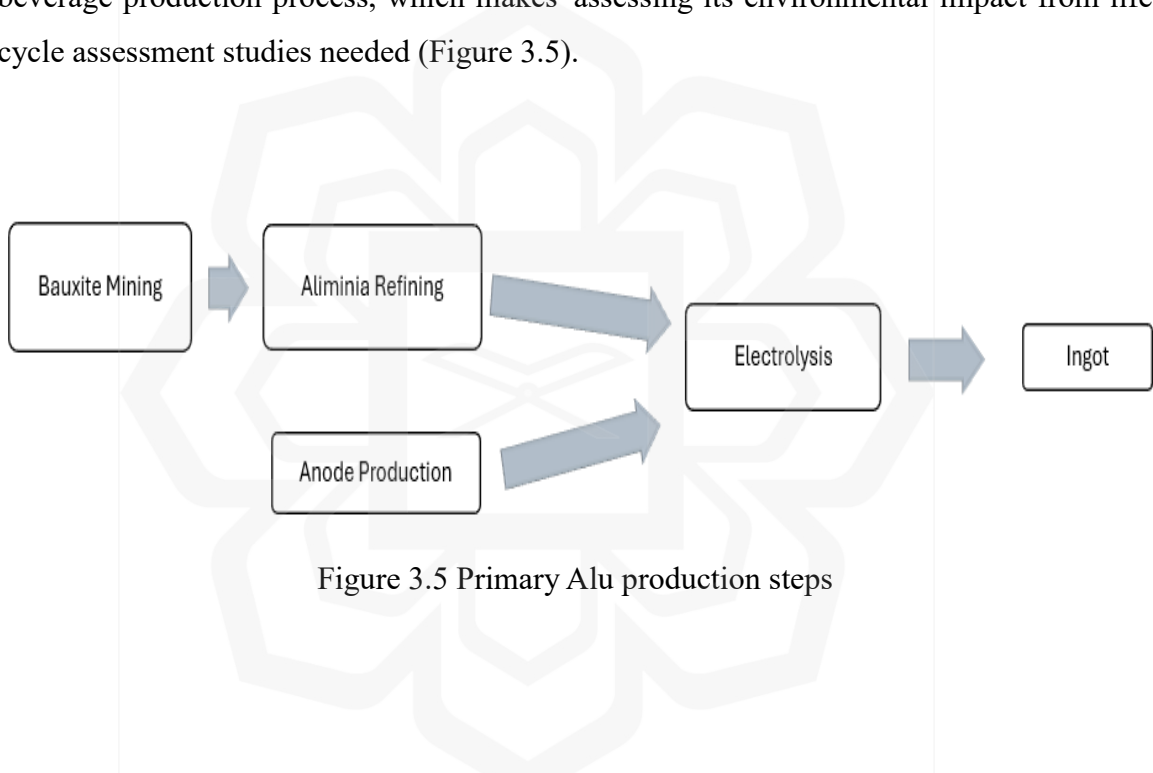


Figure 3.5 Primary Alu production steps

Alu manufacturing data is sourced directly from GREET software, which includes information from Iyer & Kelly (2022), life-cycle inventory recently updated. This paper discusses the environmental impact of the entire life cycle of Alu production in terms of energy consumption and GHG emissions. It highlights changes in industry practices and technology that impact Alu's cumulative energy demand (CED) and greenhouse gas profiles. By directly adopting the GREET model that references such revisions, this study guarantees a repeatable and accurate assessment of Alu's environmental performance in alignment with the best contemporary industry practices.

Materials in Aluminum Based Transmission System

The 36 kg cast virgin Alu based transmission system was assessed without considering cast secondary or recycled Alu. These included plastic products (2.268 kg) and styrene-butadiene rubber (2.268 kg) and were distributed among their respective pathway mixes. Figure 3.6 illustrates this where the combined weight of the system was 54 kg. Table 3.2 indicates that this data was used as input in the software to determine the environmental impacts as well as the lifecycle performance of the transmission system, highlighting the use of cast virgin Alu as the primary material. Figure 3.6 depicts the input values and pathways analyzed.

Table 3.2 Components in Alu Based Transmission System

No	Material	Weight (kg)	Remark
1.	Steel	13.608	Average steel
2.	Alu	36.000	Final shape Cast virgin Alu production
3.	Plastic Product	2.268	
4.	Styrene-butadiene Rubber	2.268	
Total		54.000	

Drag and Drop Inputs below			
<input type="radio"/> Steel	<input type="radio"/> Aluminum	<input type="radio"/> Plastic Product	<input type="radio"/> Styrene-butadiene Rubber
Quantity: 13.6078 kg	Quantity: 36 kg	Quantity: 2.2680 kg	Quantity: 2.2680 kg
Source: Pathway Mix	Source: Single Pathway	Source: Pathway Mix	Source: Pathway Mix
Pathway Mix Pathway Mix: Average Ste	Pathway Pathway: Final Shape Cast	Pathway Mix Pathway Mix: Final Averag	Pathway Mix Pathway Mix: Final Averag

Drag and Drop Main Output below
<input type="radio"/> Transmission System/Gearbox
Quantity: 54 kg
Losses
Drag and Drop other Outputs Below

Figure 3.6 Input values and pathways for Alu based transmission system

3.2.2 Primary Magnesium Production

The Mg production process starts with the extraction of raw materials, which in most cases, derive from dolomite or seawater. Extraction of raw Mg compounds done through mining or seawater brines for further processing. These processes are energy-intensive and lead to the emissions and by-products that vary on the source and extraction method.

During the materials production phase, Mg undergoes either electrolysis or thermal reduction techniques to extract elemental Mg. The electrolysis method utilises molten Mg chloride, while the thermal method is more often using dolomite as a feedstock, reducing it with ferrosilicon at elevated temperatures. After processing from material, it is used for manufacturing of parts, such as die casting and rolling of sheet, which will be used for making light-weight components such as vehicle parts (see Figure 3.7).

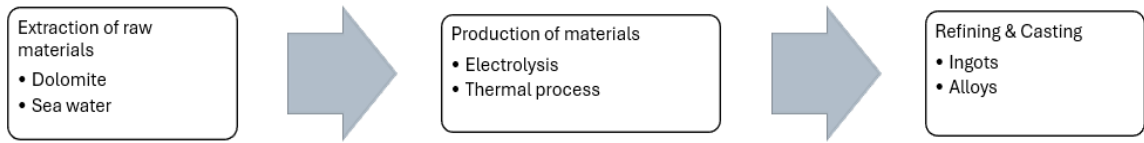


Figure 3.7 Primary Mg production steps

There are 2 main processes for the production of Mg. In the thermal production process, referred to as the Pidgeon process, dolomite is reduced with silicon in a high-temperature furnace. In the electrolytic production process, Mg is extracted from Mg chloride via the process of electrolysis, which requires an enormous input of electricity. One way is to take a combined production approach, using thermal and electrolytic methods together to leverage the strengths of both, creating efficiencies and lowering emissions. These processes supply the LCI data required for this study to assess the environmental impacts of Mg.

M.C. Johnson & J.L. Sullivan (2014)'s information on Mg manufacture, which takes into account both the thermal (Pidgeon) and electrolytic processes, is taken into consideration by GREET. This is further enhanced by the thermal process's reliance on coal and ferrosilicon, which raises energy consumption (393 MJ/kg) and greenhouse gas (GHG) emissions. However, the electrolytic process uses natural gas, electricity, and Mg chloride, which results in reduced energy intensity (308 MJ/kg) and GHG emissions by directly referencing GREET software, which integrates the data and analysis from this paper, the study ensures accurate and comprehensive assessment of CED and GHG emissions for Mg production.

Materials in Magnesium Based Transmission System

1. Magnesium Via Electrolytic Production

The system was analyzed, in this case the Mg-based transmission system, focusing on virgin Mg produced through thermal production (23 kg) and not taking into account recycled or secondary Mg. The supporting materials consist of 13.6078 kg of steel and 2.268 kg of plastic products and styrene-butadiene rubber, which were categorized under their associated pathway mixes as demonstrated in Table 3.3. Figure 3.8 shows that the system's overall weight had been adjusted to 41 kg in response to the change of Mg with Alu material. The input values and material pathways were depicted visually through the figure which illustrates the overview of the material composition and environmental impact assessment of the Mg-based system.

Table 3.3 Components in Mg (Via Thermal Production) Based Transmission System

No	Material	Weight (kg)	Remark
1.	Steel	13.6078	Average steel
2.	Mg	23	Production of virgin Mg (Thermal Production)
3.	Plastic Product	2.268	
4.	Styrene-butadiene Rubber	2.268	
Total		41	

Drag and Drop Inputs below							
<input type="radio"/> Steel	<input type="radio"/> Magnesium	<input type="radio"/> Plastic Product	<input type="radio"/> Styrene-butadiene Rubber				
Quantity	13.6078 kg	Quantity	23 kg	Quantity	2.2680 kg	Quantity	2.2680 kg
Source	Pathway Mix	Source	Single Pathway	Source	Pathway Mix	Source	Pathway Mix
Pathway Mix	Pathway Mix: Average Ste	Pathway	Pathway: Production of Vin	Pathway Mix	Pathway Mix: Final Averag	Pathway Mix	Pathway Mix: Final Averag
Drag and Drop Main Output below							
<input type="radio"/> Transmission System/Gearbox Quantity 41 kg <input type="button" value="Losses"/>							
Drag and Drop other Outputs Below							

Figure 3.8 Input values and pathways for Mg based transmission system

2. Magnesium via Electrolytic Production

The virgin Mg used for the electrolytic process (23 kg) was also not included a share of recycled or secondary Mg in the analysis of the Mg-based transmission system. Supporting materials were unchanged: steel (13.6078 kg) together with plastic products (2.268 kg) and styrene-butadiene rubber (2.268 kg), belonging to the respective pathway mixes. As shown in Figure 3.9 and Table 3.4, the total total mass was set to 41 kg. This also gives a more visual overview of the input materials and pathways while highlighting the electrolytic Mg in the environmental and lifecycle results.

Table 3.4 Components in Mg (Via Electrolytic Production) Based Transmission System

No	Material	Weight (kg)	Remark
1.	Steel	13.6078	Average steel
2.	Mg	23	Production of virgin Mg (Electrolytic Production)
3.	Plastic Product	2.268	
4.	Styrene-butadiene Rubber	2.268	
Total		41	

The screenshot displays a software interface for configuring material inputs and outputs. At the top, it says "Drag and Drop Inputs below". There are four input categories, each with a radio button and a quantity field:

- Steel:** Quantity 13.6078 kg, Source: Pathway Mix, Pathway: Pathway Mix: Average Ste
- Magnesium:** Quantity 23 kg, Source: Single Pathway, Pathway: Pathway: Production of Vir
- Plastic Product:** Quantity 2.2680 kg, Source: Pathway Mix, Pathway: Pathway Mix: Final Averag
- Styrene-butadiene Rubber:** Quantity 2.2680 kg, Source: Pathway Mix, Pathway: Pathway Mix: Final Averag

Below these is a section for "Drag and Drop Main Output below". A red box contains the main output configuration:

- Transmission System/Gearbox:** Quantity 41 kg, Losses button.

At the bottom, it says "Drag and Drop other Outputs Below".

Figure 3.9 Input Values and Pathways for Mg (Via Electrolytic Production) Based Transmission System

3. Magnesium via Electrolytic and Thermal Production (combined)

The Mg-based transmission method was substantiated with two production pathways for virgin Mg: thermal process and electrolytic production, each of which accounted for 11.5 kg in the total Mg input of 23 kg. Supporting materials were consistent in either pathway with steel (13.6078 kg), plastic products (2.268 kg), and styrene-butadiene rubber (2.268 kg). The overall weight of the system was 41 kg, as presented in Table 3.5 and depicted in Figure 3.10. This consolidated study stresses the same supportive materials and different base procedures for Mg, which plays a significant role within the LCA.

Table 3.5 Components in Mg (Via Electrolytic and Thermal Production) Based Transmission System

No	Material	Weight (kg)	Remark
1.	Steel	13.6078	Average steel
2.	Mg	11.5	Production of virgin Mg (Thermal Production)
3.	Mg	11.5	Production of virgin Mg (Electrolytic Production)
4.	Plastic Product	2.268	
5.	Styrene-butadiene Rubber	2.268	
Total		41	

Figure 3.10 Input Values and Pathways for Mg (Via Electrolytic & Thermal Production) Based Transmission System

3.2.3 Use Phase Data

REET software was employed in the use phase analysis, also referred to as the PTW phase to calculate GHG emissions and energy consumption for vehicles with Alu-based and Mg-based transmission systems. Using E10 gasoline as the energy source and with a lifetime vehicle mileage of 360,000 km, Figure 3.11 depicts the detailed fuel cycle panel setup for the Alu-based transmission system. Parameters such as operational and others were made similar across the comparative analysis. The example is from the Alu-based transmission system, but the same operational settings were used to make a direct comparison with the Mg-based transmission system.

The various key maintenance items vehicle component data for both systems is summarized in Table 3.6. Keeping these two systems similar, maintenance items such as battery weight (10.6141 kg) and engine oil weight (3.8555 kg) were the same between both the Alu and Mg systems as well as identical replacement frequencies. The single significant variation is in total vehicle weight — 1327 kg at 50-50 split for the Mg system, 1340 kg

with the Alu-based. This 13 kg saved is due to the Mg transmission (41 kg) compared to the Alu one (54 kg). Other parts like the vehicle body, powertrain and chassis were similar for both systems. In this part of the analysis, we demonstrate that the weight reduction afforded by the use of Mg could lead to improved lifetime fuel economy and lower environmental impact of the vehicle over its lifetime.

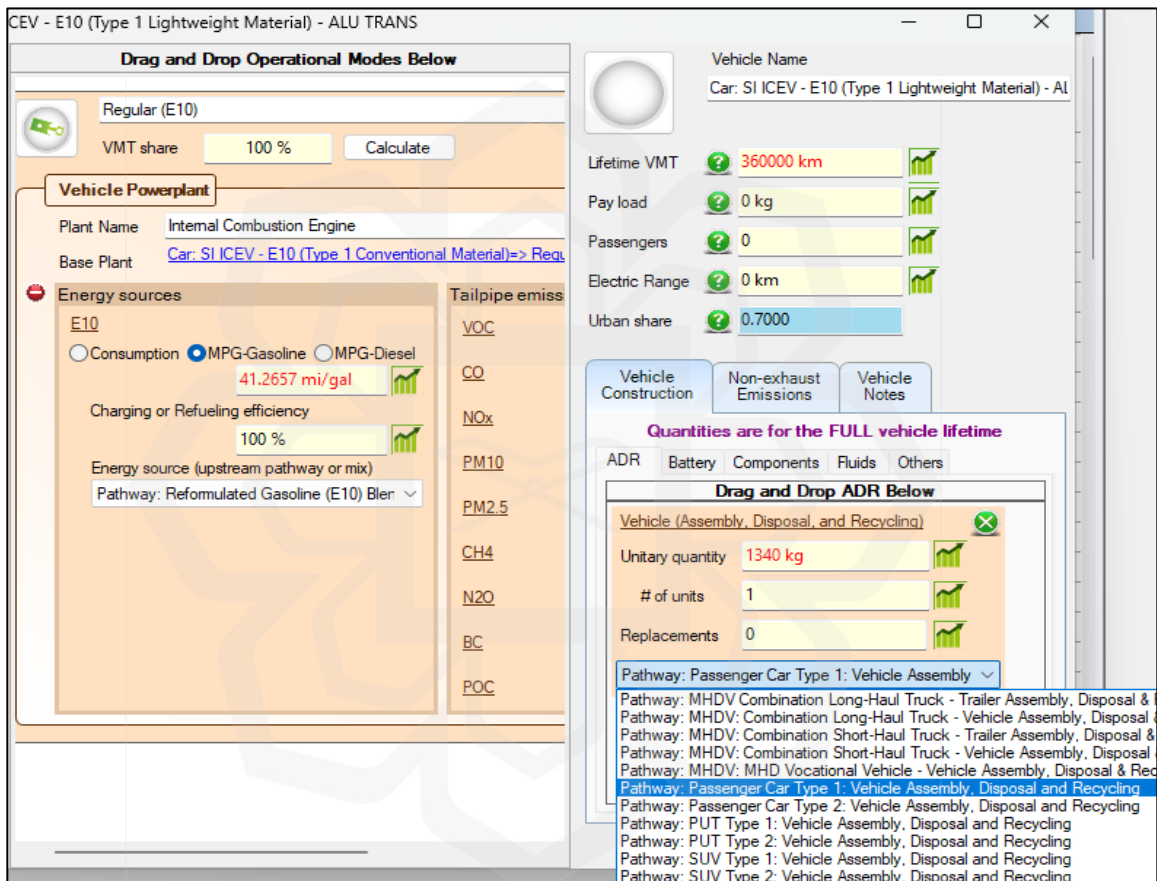


Figure 3.11 Detailed Fuel Cycle Panel Setup for the Alu-Based Transmission System

Table 3.6 Details of Maintenance and Components in Alu and Mg Based Transmission System

No	Items	Weight for Alu Transmission (kg)	Weight for Mg Transmission (kg)	Replacements	
1	Maintenance	Battery	10.6141	10.6141	5
		Engine Oil	3.8555	3.8555	39
		Power Steering Fluid	0.9072	0.9072	6
		Brake Fluid	0.9072	0.9072	6
		Transmission fluid	4	4	6
		Engine Coolant	10.4326	10.4326	6
		Windshield Fluid	2.7216	2.7216	19
		Adhesive	13.6078	13.6078	0
2	Components	Vehicle Body	646.7091	646.7091	0
		Powertrain system	334.3084	334.3084	0
		Transmission system	54	41	0
		Chassis	268.6953	268.6953	0
		Tire Replacement	36.2872	36.2872	4
	Total Vehicle Weight	1340	1327	NA	
3	Assemble, Dispose, Recycle (ADR)	1340	1327	NA	

3.3 LIFE CYCLE IMPACT ASSESSMENT (LCIA)

3.3.1 Energy and Emissions Data Analysis

The phase is to evaluate the data obtained in the inventory phase to determine its environmental impact. It assesses the emissions, energy use and other factors to determine the impact of each step in the lifecycle. The carbon footprint of the materials and energy consumed in the cycle will be compared between the 2 types of materials in this study. The (lifetime) greenhouse gas emissions per vehicle is defined as:

$$C_{LC} = C_{Mat} + C_{Par} + C_{Use} + C_{End} \quad (5)$$

and the life cycle energy usage is define as:

$$E_{LC} = E_{Mat} + E_{Par} + E_{Use} + E_{End}. \quad (6)$$

The formula for LCA measures GHG emissions and energy consumption in every step of a product's life cycle. The total life cycle GHG emissions (C_{LC}) are calculated as the sum of emissions from the material production stage (C_{Mat}), parts manufacturing stage (C_{Par}), use stage (C_{Use}), and end-of-life stage (C_{End}). Likewise, the total life cycle energy (E_{LC}) is the sum of energy consumption found in these same stages (E_{Mat} , E_{Par} , E_{Use} , E_{End}). It establishes a systematic approach to LCA that forms a basis for environmental and energy quantification of a product. Data for each stage is obtained from reliable sources, e.g., GREET 2023, making it reliable and consistent.

In this project, the analysis extends across both the vehicle and the transmission product systems with clearly defined boundary for each. The major boundaries of the emission are for the life cycle of the vehicle product system and the energy consumption for all processes of material harvesting, material manufacture, use phase, ADR as well as maintenance on a per vehicle basis. The other automotive transmission product system considers the life cycle emission of material extraction, material manufacture, use phase,

and ADR per transmission unit since maintenance is excluded. This approach ensures a better understanding of the environmental impacts for each system.

Material Extraction & Production Phase Analysis

This material extraction and production phase of both Mg and Alu is important because it contributes to the main energy consumption and resulting GHG emissions related to raw material extraction and preprocessing, and production of the material. GREET allows for the characterization of energy and emissive requirements for the early lifecycle stages to help understand environmental impacts.

Processes Analyzed:

1. Mg Production:

- Thermal Production: This process extracts Mg via thermal means, which may involve mining magnesite ore or extracting from seawater, calcining to form Mg oxide, and refining thereafter
- Electrolytic Production: This method uses electrolysis to refine Mg, its energy-intensive nature, and the emissions it produces.
- Combined Production: Thermal-electrolytic combined production.

2. Alu Production:

- Conventional Production: Include bauxite mining, alumina refining, and smelting processes to produce Alu oxide.

Data Analysis Approach:

The article includes a comparison of Mg and Alu production processes prepared for the production of transmission system under different scenarios. Each process will be evaluated against the following key metrics:

Energy Consumption:

- Total energy usage (in MJ).
- Contributions from specific energy sources such as natural gas, coal, petroleum, and etc.

Greenhouse Gas Emissions:

- CO₂ equivalent emissions (kg CO₂/kg) (GHG Emission).
- Other atmospheric pollutants, such as carbon monoxide (CO), sulfur dioxide (SO₂), methane (CH₄), and nitrogen oxides (NO_x).

Based on Table 3.7, the functional analysis focuses on evaluating the energy consumption and emissions across different lifecycle stages for Alu and Mg. The table presents sample data for Alu, while similar data will be extracted for Mg produced through thermal, electrolytic and combined production methods. For the material extraction and production phase, the study assesses Alu's energy use and emissions per kilogram and per 36 kilograms, and Mg's energy and emissions per kilogram for each production method (thermal, electrolytic, and combined). For the production of Alu transmission components, energy consumption and emissions will be analyzed for 1 kilogram and 54 kilograms of transmission material.

Additionally, the analysis includes the assembly, recycling, and disposal phases for a 1,340-kilogram vehicle (equipped with Alu transmission), along with the use phase over 360,000 kilometers. The analytical framework emphasizes calculating the total energy

consumption and emissions for each phase to identify trade-offs between Mg and Alu. This involves comparing the environmental impacts of different production methods for Mg and evaluating its lifecycle performance against Alu. The findings will help determine Mg's feasibility as a lightweight material for automotive applications by balancing production-phase emissions with use-phase benefits.

Table 3.7 Alu Production Data for Transmission System

Items		Alu			Assembly, Dispose, Recycle (ADR) (per 54 kg)
		Material extraction and production (per 1kg alu)	Production of transmission (per 1kg)	Production of transmission (per 54 kg)	
Energy	Total (MJ)	146	110.35	5958.73	891.1094
Selected Atmospheric Emissions	CO ₂ (KG)	8.8802	6.7631	365.21	50.4715
	CO (KG)	0.003669	0.0075	0.41	0.0320
	SOX (KG)	0.02675	0.0207	1.12	0.0224
	CH ₄ (KG)	0.01568	0.0125	0.67	0.1285
	NOX (KG)	0.008262	0.0065	0.35	0.0484
Total GHG Emission	GHG Emission (KG CO ₂ eqt/KG)	9.739	7.4129	400.30	54.7076

Use Phase Analysis

The use phase analysis assesses the environmental effects, primarily GHG emissions and energy consumption, throughout the vehicle's use. Vehicle lifetime energy consumption savings potential due to the difference in weight of Alu versus Mg transmission systems will be examined.

Key Formula and Calculations

The relationship between vehicle weight and fuel consumption is expressed using the FRV, which quantifies fuel savings per 100 km of driving for every 100 kg of weight reduction. The formula is as follows:

$$\Delta F = FRV \cdot \frac{\Delta W}{100} \quad (7)$$

Where:

- ΔF : Fuel saved (liters per 100 km).
- FRV: Fuel reduction value (L/100 km per 100 kg), typically ranging from 0.15–0.25 without powertrain adjustment (Kelly et al., 2015).
- ΔW : Weight difference between Al and Mg transmission systems.

Using GREET 2023 data; the weight of the Mg transmission system is approximately 30% lighter than its Alu counterpart. For instance:

- Alu transmission weight: $W_{Al} = 54$ kg
- Mg transmission weight: $W_{Mg} = 41$ kg
- Weight difference: $\Delta W = W_{Al} - W_{Mg} = 13$ kg.

The weight difference directly impacts fuel consumption reduction, which is further related to the vehicle's Vehicle Miles Traveled (VMT) over its lifetime.

The fuel savings during the use phase can be calculated as:

$$\text{Total Fuel Saved (L)} = \Delta F \cdot \frac{\text{VMT}}{100} \quad (8)$$

Substituting the values:

- FRV = 0.25 L/100 km per 100 kg
- $\Delta F = 0.25 \times 13/100 = 0.0325 \text{ L/100 km}$

Total fuel saved over 360,000 km:

$$\text{Total Fuel Saved} = 0.0325 \times 360,000/100 = 117 \text{ L}$$

$$\begin{aligned} \text{New Fuel Consumption} &= \text{Initial Fuel Consumption} - \text{Fuel Savings} \\ &= 5.7 \text{ L/100km} - 0.0325 \text{ L/100km} = 5.67 \text{ L/100km} \end{aligned} \quad (9)$$

The fuel consumption due to 1 kg of the component is calculated as:

$$F = K \times \frac{L}{M_V} \quad (10)$$

Where:

K = Fuel consumption (L/100 km)

L = VMT (km)

M_V = Vehicle curb weight (kg)

Calculation for Alu Transmission:

Vehicle Weight: 1340 kg

Component Weight: 54 kg

Fuel Consumption per kg:

$$F_{Al} = \frac{5.7}{100} \times \frac{360,000}{1340} = 15.31 \text{ L/kg.}$$

Total Fuel Consumption:

Total Fuel (Al) – 15.31 L/kg x 54 kg = 826.74 L

Calculation for Mg Transmission:

Vehicle Weight: 1327 kg

Component Weight: 41 kg

Fuel Consumption per kg:

$$F_{Mg} = \frac{5.67}{100} \times \frac{360,000}{1327}$$
$$F_{Mg} = 15.39 \text{ L/kg.}$$

Total Fuel Consumption:

Total Fuel (Mg) = 15.39 L/kg x 41 kg = 631 L

The total GHG emissions and energy consumption in use phase will be measured by using the fuel consumption per kg obtained above.

Assumptions

- Maintenance activities, such as fluid changes, are assumed to have no difference between Al and Mg systems. Table 3.6 as shown earlier, provide the detail of maintenance activities for VMT 360000 km.
- The fuel economy improvement is solely based on the weight reduction of the transmission system, with no adjustments for powertrain efficiency.
- No secondary weight savings (e.g., in braking or suspension systems) are included.

3.3.2 Trade-Off Analysis

This analysis targets the production, use and ADR phases of the product life cycle which provide substantial differences in environmental impacts between the Mg and Al transmission system components. Material extraction emissions are encompassed within the production phase, where mining, refining, and manufacturing processes yield greater emissions for Mg than for Al. The use phase is where this lightweighting has the greatest impact on fuel consumption and associated emissions, because of the weight differential between vehicles with the lighter Mg transmission and those with the heavier Al transmission. Next, the ADR phase takes into consideration the variations in energy use and emissions during assembly, recycling, and disposal that arise due to the differing weights of the Mg and Al components. The analysis focuses on the production, use and ADR phases in the material life cycle, which also reveals trade-offs, especially on one side, Mg's higher production emissions but lower emissions in use and ADR phases on the other side, contributing to a more detailed comparison of materials' full life cycle impacts.

To find the break-even distance, a graph is constructed, with cumulative GHG emissions and total energy consumed plotted on the y-axis (in kg CO₂-eq), and vehicle distance traveled plotted on the x-axis (in kilometers). Emissions estimates for each material are made at various mileage intervals (50,000 km, 100,000 km all the way up to 400,000 km). The data to examine the break-even distance for GHG emission and total energy used, can be found on Table 3.8. Emissions during the production phase are constant, determining the point of departure (y-intercept) of each line, while the slope describes the emissions of the use phase per kilometer driven. The crossing of the cumulative emissions lines for Mg and Al represents the break-even distance. At this stage, Mg and Al components contribute the same emissions. This vectors approach gives a transparent and impactful way to visualise environmental trade-offs of those materials throughout a timeframe of a car's lifetime.

Table 3.8 Data for Trade off analysis on GHG Emission

Parameter	Transmission Types	Use Phase (PTW)	Material & Components Production	Assembly, Disposal & Recycle (ADR)	Total
GHG Emissions - kg CO ₂ -eqt / Transmission	Alu	1770.87	400.32	54.71	2225.90
	Mg E	1351.58	924.84	41.53	2317.95
	Mg T	1351.58	1122.84	41.53	2515.95
	Mg C	1351.58	1023.84	41.53	2416.95

3.4 INTERPRETATION

The interpretation phase of this LCA focuses on the two main objectives of the study. First, it looks at the overall environmental impacts of Mg and Alu transmission systems across their entire life cycle, from material extraction to vehicle disposal. This includes understanding the higher emissions from Mg production compared to Alu and the benefits of Mg's lighter weight.

Second, the interpretation balances the higher production emissions of Mg against its potential for fuel savings and emissions reductions in the vehicle's use phase. The results also mark the break-even distance, at which Mg becomes either a better option than Alu or vice versa. The study will interpret these results to demonstrate which material performs better in terms of environmental sustainability of vehicle's transmission systems meanwhile being able to fulfill the aims of study.

CHAPTER FOUR

RESULT AND DISCUSSION

4.1 TRANSMISSION PRODUCT CYCLE

4.1.1 Total Energy Consumption per Transmission

The major finding from Figure 4.1 indicates that Mg transmissions have a lower impact than Alu transmissions. The total use of energy by Mg transmission systems showed lower values of energy with a percentage between 16.66% and 17.42% as cumulated energy figures were 27,006 MJ (Mg Electrolytic) and 27,253 MJ (Mg Thermal) while Alu consumed the most energy of 32,702 MJ. Such phenomena point out that Mg has a strong energy advantage due to its energy consumed during the use of the product which is lower than that of Alu at 19,731 MJ instead of 25,852 MJ (for Alu) potentially further demonstrates the weight advantages of Mg in car transmission applications.

Furthermore, the advantages of Mg transmissions are also noticeable in the ADR phase, where the value is 677 MJ for Mg and 891 MJ for Alu. Nonetheless, the lightweight nature of Mg allows for more energy recovery when recycling, making it more efficient overall. This attributes not only aligns with sustainability objectives but also plays a role in reducing reliance on the energy-intensive process of virgin material production. The results underscore the suitability of Mg for use in transmission systems in terms of both energy use and lifecycle sustainability. Since the product lifecycle energy consumption is lower, Mg presents itself as an attractive option for reducing the environmental impact of automotive transmissions.

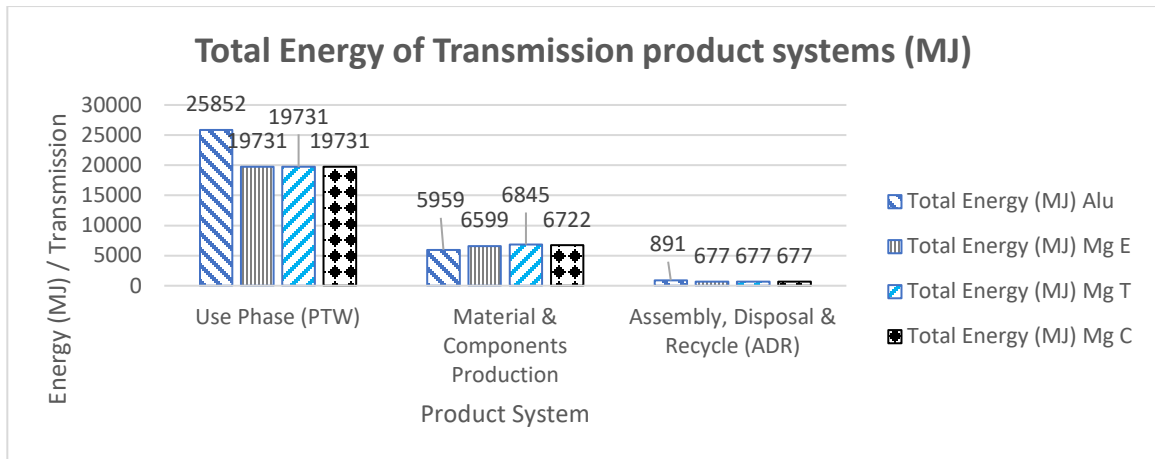


Figure 4.1 Total Energy Consumption of Transmission Product System

4.1.2 Total Energy from Different Energy Type

As can be seen in Figure 4.2, Mg has significant energy benefits over Alu systems in a transmission system. In Mg systems, the total energy requirement is always lower than Alu with Mg Electrolytic (MG E), Mg Thermal (MG T) and Mg Combined (MG C) requiring 46,737 MJ, 46,984 MJ, and 46,860 MJ, respectively; Alu requires 58,554 MJ. The lower total energy use (20% lower in Mg systems, for example) highlights the energy efficiency of the choice of material, Mg, itself. The difference is mainly a result of Mg's lower dependence on coal-based energy, as MG E and MG T use coal as a source of energy estimated to be 21,036 MJ and 24094 MJ, respectively, much lower than the 27,888 MJ used for Alu. Lower reliance on coal makes Mg systems compatible with cleaner energy profiles and therefore reduces environmental impacts even more.

In addition to the lower coal-based energy use, Mg also has lower energy use associated with petroleum fuel use. These differences are shown as a decreased amount of petroleum fuel used by the Mg Electrolytic and Mg Thermal systems, for which 19,884 MJ and 20,336 MJ is consumed, respectively, compared to Alu at 26,463 MJ. This reduction in petroleum fuel consumption during the lifecycle of Mg transmissions was found to be

25% which indicates these materials can enhance the energy sustainability of automotive applications. Despite the higher natural gas consumption in Mg E (5,058 MJ) than in Alu (2,371 MJ), the overall energy savings and lower reliance on fossil fuels mean that Mg is the more environmentally friendly material for use in transmission systems. These results strengthen the case for Mg use in lightweight automotive designs, especially in terms of minimizing the environmental and energy burdens that arise from transmission systems.

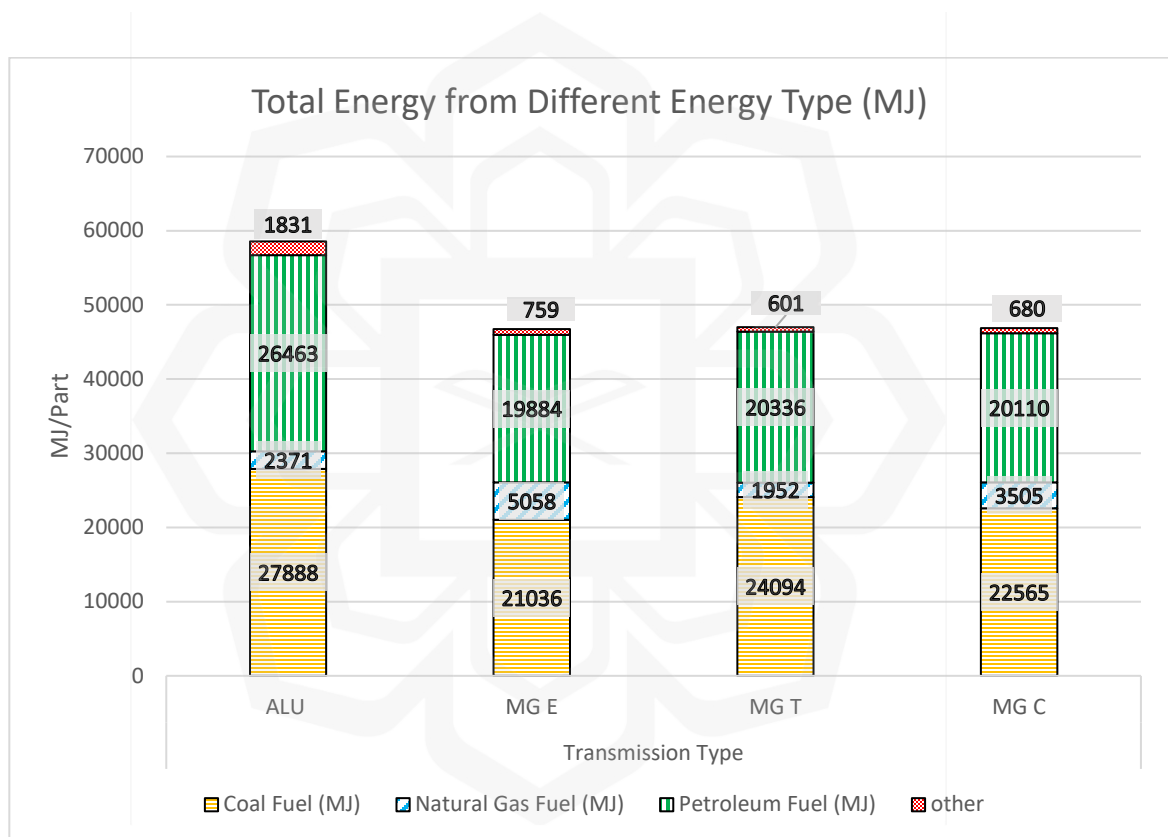


Figure 4.2 Total Energy from Different Energy Type

4.1.3 Selected Atmospheric Emissions for Transmission Production

The emission data presented in Figure 4.3 shows a range of environmental impacts for Alu and Mg transmissions depending on the emission type. In terms of total emissions, Mg

Thermal (MG T) has the most emissions at 2.965 kg/transmission, followed by Mg Combined (MG C) at 2.560 kg, and Mg Electrolytic (MG E) at 2.154 kg, with Alu being the lowest at 2.548 kg. Concerning certain emissions, the Mg systems have relatively higher concentrations of CO and CH₄ while the Mg Electrolytic exhibits the highest value for CH₄ emissions at 0.990 kg. For SO_x emissions though, all Mg types, especially Mg Electrolytic (0.287 kg) are significantly lower than Alu (1.116 kg).

These results indicate that Mg has a significant environmental benefit compared to Alu in specific emission categories. SO_x emission gains, in particular, appear most pronounced across all Mg production methods, most significantly against Alu (1.116 kg/transmission) as seen with Mg Electrolytic (0.287 kg/transmission). At over 74% reduction, this demonstrates Mg's ability to improve air quality, particularly in areas with sulfur dioxide emissions control requirements. The reliance on hydroelectric energy in the electrolytic process largely drives this advantage, showing the importance of clean energy inputs in reducing the environmental impact of material production. While Mg systems produce more emissions like CO and CH₄, these are balanced by the overall lower emissions of Mg Electrolytic (2.154 kg/transmission) compared to Alu (2.548 kg/transmission).

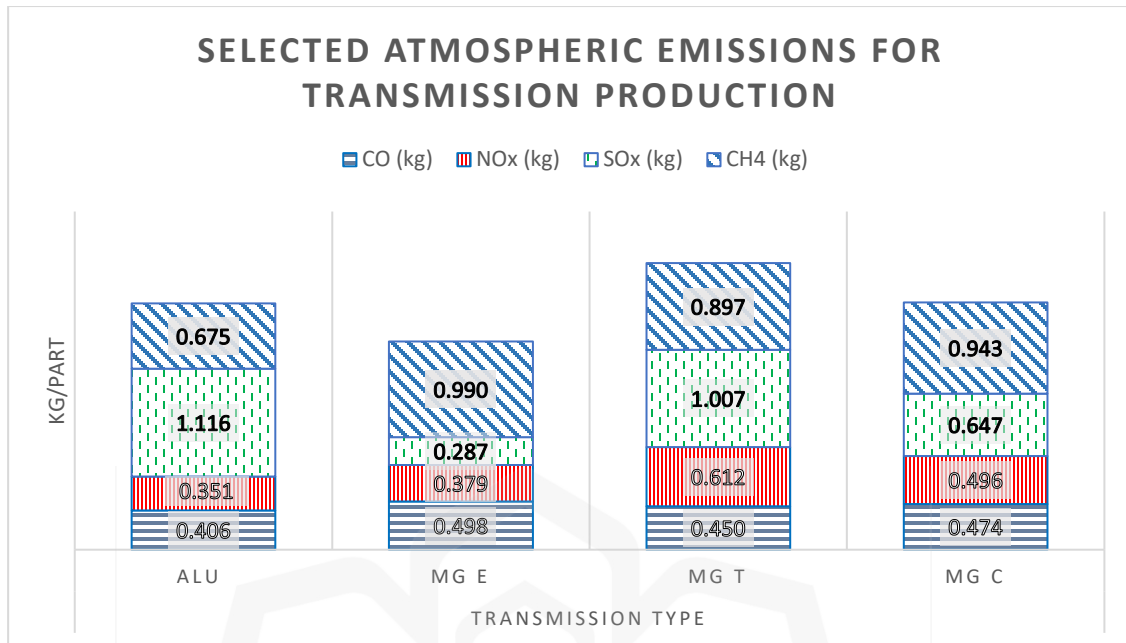


Figure 4.3 Selected Atmospheric Emissions for Transmission Production

4.1.4 Total CO₂ Emissions for Different Transmission Types

The findings for Figure 4.4 show that magnesium (Mg) transmission systems demonstrate significant advantages over their aluminum (Alu) counterparts in terms of total CO₂ emissions over the entire lifecycle. Total CO₂ emissions for Mg Electrolytic (MG E) is 1,874 kg, Mg Thermal (MG T) is 2,105 kg, Mg Combined (MG C) is 1,990 kg and Alu is 2,269 kg. This represents a 17.4% Mg Electrolytic, 7.2% Mg Thermal and 12.3% Mg combined reduction from Alu. The largest part of these savings are achieved in the use phase (PTW), with Mg systems consistently considering 1,413 kg of CO₂ versus 1,851 kg for Alu (23.6% reduction in the use phase), because of Mg's lightweight properties and its effect on fuel consumption and emissions during driving.

Apart from the use-phase benefits, Mg systems are competitive also in the other phase of the lifecycle. While accounts for higher production phase emissions of Mg

Thermal systems (654 kg), emissions of Mg Electrolytic (423 kg) and Mg Combined (539 kg) systems are lower or comparable. Additionally, ADR phase emissions for Mg are consistently lower at 38 kg than for Alu at 50 kg—a reduction of 24% in the ADR phase. These underscore Mg’s potential for achieving lower total lifecycle CO₂ emissions as compared to Alu, providing a strong interest in its implementation in lightweight and sustainable automotive transmission designs.

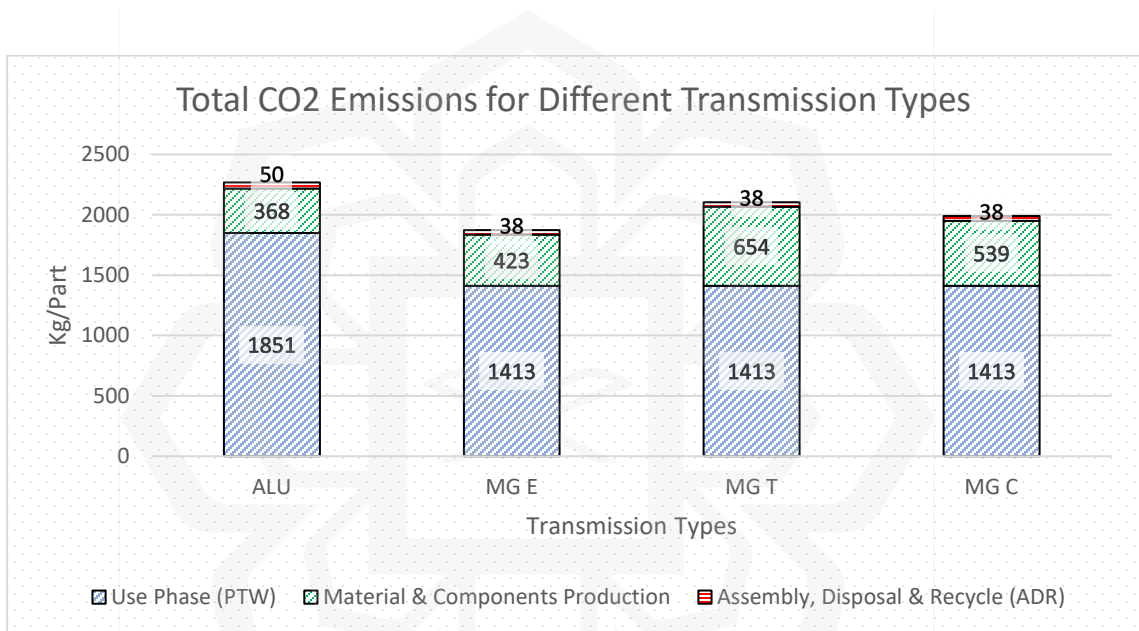


Figure 4.4 Total CO₂ Emissions for Different Transmission Types

4.1.5 GHG Emissions per Transmission

As shown in the results of Figure 4.5, the emissions over the life cycle of Mg transmissions are the highest compared to Alu transmissions. Alu would be 2,226 kg CO₂-eq, the lowest all of them, and Mg systems varied from 2,318 kg CO₂-eq (Mg Electrolytic) to 2,517 kg CO₂-eq (Mg Thermal), representing rises of 4.13% to 13.07%. While Mg’s lighter material weight resulted in reduced use-phase emissions (1,352–1,354 kg CO₂-eq) compared to Alu

(1,771 kg CO₂-eq), these savings were not enough to offset the much higher production-phase emissions of Mg systems.

This mainly occurred during the phase of material production, where Mg had GHG emission values between 925 kg CO₂-eq (Mg E) and 1,123 kg CO₂-eq (Mg T), while Alu accounted for approximately 400 kg CO₂-eq. In contrast, Mg systems exhibited slightly lower emissions in the assembly, disposal, and recycling (ADR) stage (42 kg CO₂-eq) than Alu (55 kg CO₂-eq). The results reveal that, despite Mg's ability to provide improvements during the use and ADR stage through emission reductions, the production stage still needs additional investment in technologies especially in material and production phase to lower overall life cycle emissions to make it a competitive sustainable alternative to Alu in term of GHG emissions.

The difference in the trends of total energy consumption compared to GHG emissions can be explained due to the overall energy source and production process for Mg and Alu transmissions. Although Mg is relatively light and this lowers its energy consumption, the carbon intensity of Mg production is very high especially with thermal methods, resulting in notably higher GHG emissions despite lower energy usage. In comparison, Alu production typically uses cleaner forms of energy, or involves more efficient methods, resulting in less GHG emissions; even though the overall energy required to produce Alu is generally greater than for Mg. Second, the use-phase energy savings associated with Mg due to lower fuel consumption do not offset the increased GHG emissions associated with production. The gap between the GHG performance of Mg and energy consumption emphasizes an opportunity if cleaner production technologies could enhance this gap to match the energy advantages of Mg.

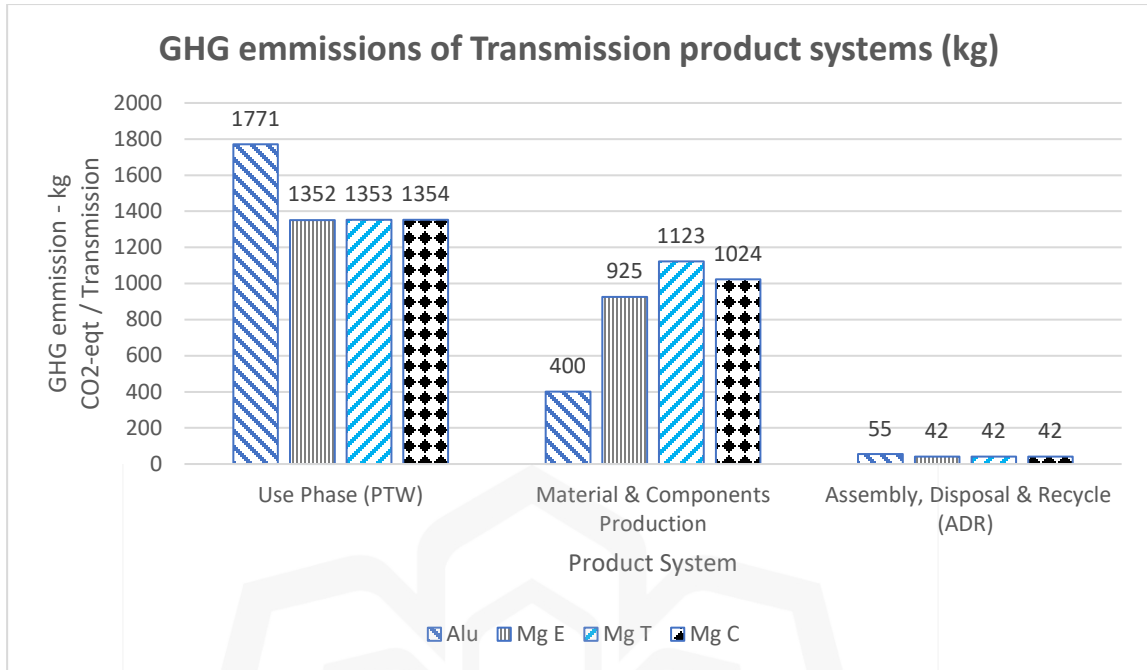


Figure 4.5 GHG Emission of Transmission Product System

4.2 TRADE-OFF ANALYSIS

4.2.1 Total Energy Break-Even Distance between Product Systems

Compared to Alu systems, Mg transmission systems display a clear total energy break-even point, underlining the outstanding lightweight energy efficiency potential of Mg as a material. As shown in Figure 4.6, the break-even point is achieved at 37,647 km for Mg Electrolytic (MG E) and at 52,118 km for Mg Thermal (MG T). These results are significantly different from those reported by Dubreuil et al. (2010), with no break-even reported for Mg in energy analysis with Alu. This difference is primarily attributable to utilizing GREET 2023 in this study, which uses updated regional production efficiencies and cleaner energy grid mixes specific to North America that substantially decreases the energy intensity of Mg production. In comparison, Dubreuil used global averages, taking

into account input data dominated by Pidgeon processes which rely on coal, resulting in an increased Mg production energy footprint.

The energy used in this study, as modeled by GREET 2023, reflects advancements in electrolytic and thermal Mg production technologies, with energy consumption for Mg Electrolytic (267 MJ/kg) and Mg Thermal (256 MJ/kg) being significantly lower than Dubreuil's reported values of 308 MJ/kg for electrolytic Mg (assumed under an Australian grid mix) and 393 MJ/kg for Pidgeon-process Mg. These differences in LCA data sources and assumptions, particularly Dubreuil's reliance on older global averages with a heavy emphasis on coal-based production, explain why Mg in Dubreuil's analysis does not achieve a break-even point despite its weight reduction benefits.

Additionally, Dubreuil's evaluation distance of 200,000 km limited the opportunity for Mg's lower use-phase energy to compensate for its higher production energy. In contrast, this study extended the analysis to 360,000 km, allowing Mg's weight-driven fuel savings during the use phase to offset its initial energy-intensive production. These findings emphasize that regional, updated data (e.g., GREET 2023) and longer evaluation scopes of VMT are critical for accurately assessing the lifecycle performance of lightweight materials like Mg. With its ability to reduce both use-phase energy and some lifecycle emissions, Mg demonstrates clear advantages over Alu for automotive transmission systems, particularly when the weight difference is increased. The majority of Mg's advantages over Alu come from the use phase, where the reduced weight of Mg transmissions significantly lowers fuel consumption and energy demand during vehicle operation.

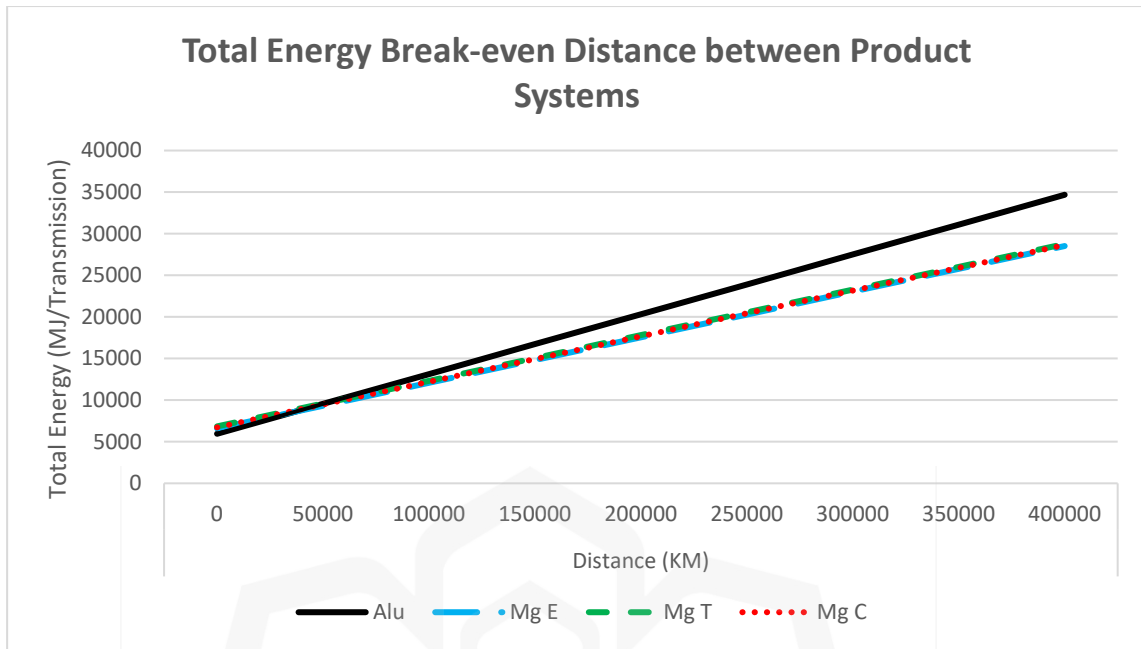


Figure 4.6 Relation between the Total Energy Consumption and Driving Distance for Various Transmission System

4.2.2 GHG Emission Break-Even Distance between Product Systems

This study is consistent with the findings of Dubreuil et al. (2010) study, confirming that neither magnesium (Mg) nor aluminum (Alu) reach a break even point in GHG-emissions as shown in Figure 4.7. Similar to Dubreuil's observations, high production emissions of Mg dominate over the use-phase savings net of VMT (360,000 km for this study compared to 200,000 km for Dubreuil's). The weight reduction achieved in this study aligns with Dubreuil's findings, where trimming the front-end assembly weight from 61.0 kg (Alu) to 45.2 kg (Mg) resulted in a significant 15.8 kg reduction. Likewise, this work reports a 33% weight reduction when comparing a 54 kg (Alu) and 41 kg (Mg) transmission systems.

Mg exhibits a greater life cycle GHG emissions than Alu across all scenarios tested. The emissions for Alu transmission systems amount to 2225.90 kg CO₂-eq per unit, whereas Mg emissions fall between 2317.95 kg CO₂-eq (Mg E) and 2515.95 kg CO₂-eq (Mg T), a 4.1%-13.1% increase in comparison with Alu. The difference is mainly caused by the higher production emissions for Mg (especially for the thermal process: 1122.84 kg CO₂-eq for Mg versus 400.32 kg CO₂-eq for Alu). Though it does have lower emissions during the use-phase (1351.58 kg CO₂-eq for Mg compared to 1770.87 kg CO₂-eq for Alu), the production-versus-use-phase emissions trade-off doesn't achieve a breakeven point. These results highlight a potential opportunity for Mg production processes to improve their environmental performance to a level similar or higher to Alu because the gap is not really big for overall between both materials.

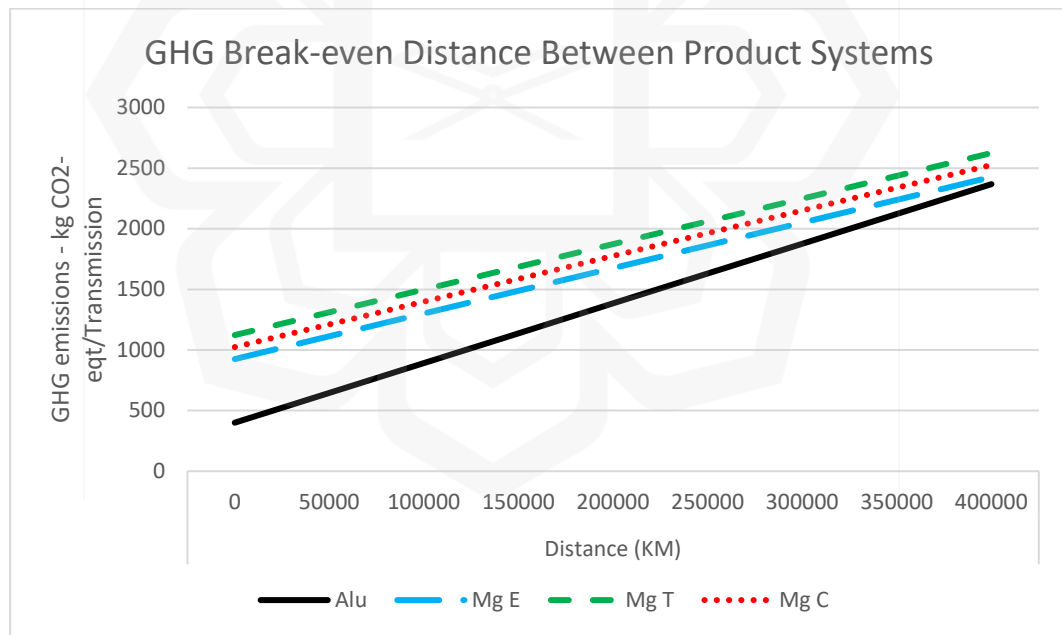


Figure 4.7 Relation between the Total GHG Emission and Driving Distance for Various Transmission System

4.3 VEHICLE PRODUCT CYCLE

4.3.1 Total Energy Consumption per Vehicle

This part evaluates the total energy consumption for vehicles equipped with different types of transmission systems (Alu and Mg) across all life cycle phases, including material extraction, production, use phase, ADR, and maintenance. Figure 4.8 shows the results for total energy of vehicles equipped with different types of transmission systems. The results indicate that Mg transmission-equipped vehicles generally consume slightly less total energy than Alu transmission-equipped vehicles. Specifically, vehicles with Alu transmissions exhibit a total energy consumption of 808,363 MJ per vehicle, whereas Mg transmissions range from 805,884 MJ (Mg Electrolytic) to 806,130 MJ (Mg Thermal). These reductions, although minimal (0.31% to 0.28% lower than Alu), primarily result from Mg's reduced use-phase energy consumption due to its lightweight properties.

Breaking down the energy consumption, Mg transmissions consistently show lower energy use in the use phase (638,613 MJ for all Mg systems compared to 641,517 MJ for Alu), while the material production phase reveals higher energy demands for Mg, particularly Mg Thermal (130,487 MJ). However, the consistent ADR and maintenance energy (37,031 MJ for all systems) ensure that the differences arise primarily from material production and use-phase contributions. These findings suggest that while Mg provides energy savings in use phase, improvements in production efficiency are also essential to enhance its overall life cycle energy performance.

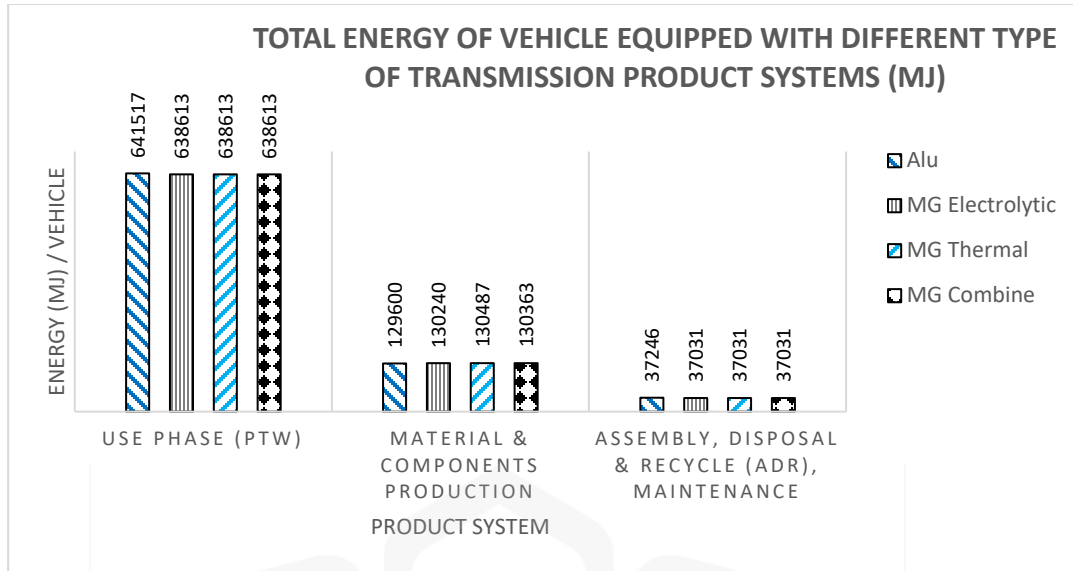


Figure 4.8 Total Energy consumption of Vehicle Product System

4.3.2 GHG Emission per Vehicle

Greenhouse gas (GHG) emissions were compared for vehicles with Alu and Mg transmissions, covering all life cycle stages like material extraction, production, use, and disposal. From results in Figure 4.9, vehicles with Alu transmissions emit total 53,579 kg CO₂-eq, while Mg transmissions emit slightly more: 53,892 kg CO₂-eq for Mg Electrolytic (0.58% higher) and 54,090 kg CO₂-eq for Mg Thermal (0.95% higher). This increase is mainly due to higher emissions during Mg production, where emissions range from 7,926 kg CO₂-eq to 8,124 kg CO₂-eq, compared to Alu's 7,402 kg CO₂-eq, which is 7.06% to 9.73% higher for Mg.

In comparison to Alu (43,944 kg CO₂-eq), Mg has lower emissions during the consumption phase (43,745 kg CO₂-eq), but the savings are insufficient to offset the higher emissions during the production phase. There is minimal variation in the ADR stages; emissions for all systems range from 2,220 kg CO₂-eq to 2,234 kg CO₂-eq. This

demonstrates the necessity of better Mg production techniques to lessen their negative effects on the environment and increase their competitiveness with Alu, particularly in the material production stage.

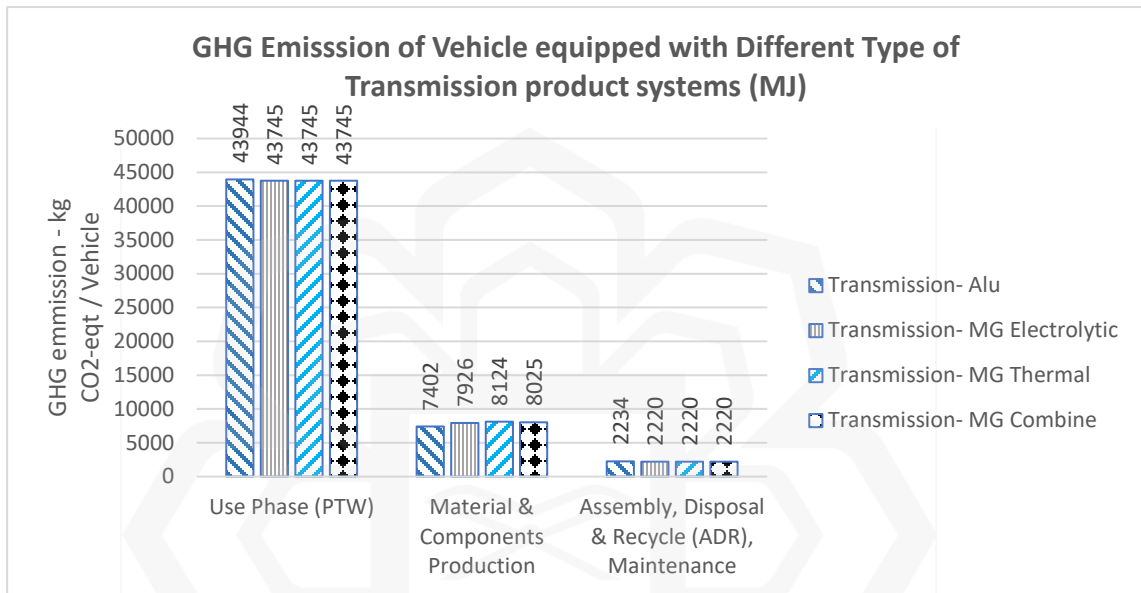


Figure 4.9 GHG Emission of Vehicle Product System

CHAPTER FIVE

CONCLUSION & RECOMMENDATION

5.1 CONCLUSION

This study meets the objective by showing that magnesium (Mg) transmissions have many advantages over aluminum (Alu), especially for weight reasons in automotive applications. The benefits become even more pronounced during the use-phase, where the lightweight characteristics of the Mg transmission have significantly lowered fuel consumption and the energy required to operate the vehicle, resulting in a 23.6% reduction in use-phase CO₂ emissions when compared to the Alu counterpart. The results indicate that, despite its high production-phase energy and GHG emissions, Mg reaches its total energy break-even distance, which are 37,647 km from Electrolytic and 52,118 km from Thermal process and is competitive in sustainable transmission designs.

Mg also holds significant advantages in total lifecycle for some selected emissions. For examples Mg Electrolytic (MG E) outputs 1,874 kg CO₂ while Alu outputs 2,269 kg CO₂ which has 17.4% less. Mg systems also have reduced emissions of key categories such as SO_x, where Mg Electrolytic emits 0.287 kg/transmission, a figure over 74% lower than the emissions for Alu at 1.116 kg/transmission, further enhancing its environmental profile. When combined with an understanding of these advantages in both energy use and emissions, it positions Mg as an excellent performing material at light weight for automotive designs. Despite challenges facing in production phase, Mg's lower total emissions for some harmful gaseous and improved performance in use phase indicate its potential for longer term sustainability.

Although Mg's comparatively higher production GHG emissions present some current challenges, advances in Mg manufacturing can also reduce Mg's environmental footprint, including the use of alternative cover gases and energy efficient processes. In about few years, these developments may lead Mg to become the primary material used in automotive transmission systems, allowing the material to outcompete Alu with its energy savings during use phase and its lower life-cycle pollution. The significance of this study reinforces the potential for Mg to contribute to the development of lightweight, energy-efficient vehicles, align with global sustainability goals.

5.2 RECOMMENDATION

To enhance the potential of magnesium (Mg) in automotive applications, future research should prioritize optimizing Mg production processes to reduce energy consumption and greenhouse gas (GHG) emissions. More studies are suggested to enhance the performance of both primary and secondary processes, for example, improved utilization of renewable energy sources or alternative cover gases instead of the highly prominent greenhouse gas, SF₆. Developments in these fronts can potentially reduce the environmental impact of Mg in the manufacturing process and make it a more sustainable material for automotive design. Additionally, further research into recycling practices and advancement of a circular economy for Mg may mitigate the material's significant impacts during production by maximizing the reuse of Mg at end of life.

Finally, later research might discuss the inclusion of Mg components in future automotive technologies, including electric and hybrid vehicles. Utilizing Mg not only increases battery efficiency but also increases vehicle mileage range; both of which are key objectives for low-impact vehicle designs. A holistic life cycle assessment (LCA) approach from cradle to cradle should be employed to analyze trade-offs between production impacts and use-phase benefits, ensuring that Mg's role in reducing overall

environmental impact is fully realized. Filling these gaps will further enable the role of Mg in terms of sustainable automotive innovations.



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